Tampere University

STEPHEN FOX

Three Fundamental Trade-offs in Expanding Sustainable Distributions of Manufacturing

Tampere University Dissertations 247

Tampere University Dissertations 247

STEPHEN FOX

Three Fundamental Trade-offs in Expanding Sustainable Distributions of Manufacturing

ACADEMIC DISSERTATION
To be presented, with the permission of
the Faculty of Engineering and Natural Sciences
of Tampere University,
for public discussion
on 23 April 2020, at 12 o’clock.

ACADEMIC DISSERTATION
Tampere University, Faculty of Engineering and Natural Sciences
Finland

Responsible supervisor and Custos	Professor Minna Lanz Tampere University Finland	
Supervisor(s)	Professor Esko Niemi Aalto University Finland	
Pre-examiner(s)	Doctor Günter Hörcher Fraunhofer IPA Germany	Professor Joost Duflou KU Leuven Belgium
Opponent	Professor Harri Haapasalo University of Oulu Finland	

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

Cover design: Roihu Inc.

ISBN 978-952-03-1550-4 (print)
ISBN 978-952-03-1551-1 (pdf)
ISSN 2489-9860 (print)
ISSN 2490-0028 (pdf)
http://urn.fi/URN:ISBN:978-952-03-1551-1

PunaMusta Oy – Yliopistopaino
Tampere 2020

ACKNOWLEDGEMENTS

The content of this dissertation is drawn from eight years of largely unfunded research, which led to the publication of scientific journal papers. The author would like to thank the editors and reviewers of the scientific journals in which the research has been published, as well as my co-authors and the more than 100 research participants. Also, the author would like to thank Responsible Supervisor, Professor Minna Lanz, and Supervisor, Professor Esko Niemi, for their guidance in preparation of the dissertation, which is based on five of the published scientific journal papers. In addition, thanks go to Päivi Vahala for support in formatting the dissertation, and to Doctoral Programme Co-ordinators, Anna Nykänen and Minna Uusitalo.

Espoo, 16 March 2020
Stephen Fox

ABSTRACT

The background of the research is the trend towards more inclusive manufacturing. This includes all levels of technologies to enable more diverse geographic and demographic distributions of manufacturing, which can improve ecological and social sustainability. Expanding distributions of manufacturing is of interest to governments, companies, communities and individuals. Interest among government and companies relates to manufacturing being re-shored and re-distributed. Interest among communities and individuals is in people having more involvement in the production of what they consume: i.e. prosumption. Expansion of geographic distributions has potential to increase ecological sustainability, for example, by reducing long-distance transportation. Expansion of demographic distributions has potential to increase social sustainability, for example, by increasing the diversity of people involved in manufacturing. The dissertation addresses three research gaps concerned with sustainable distributed manufacturing. In particular, the fundamental challenges of three manufacturing trade-offs are addressed as follows: product originality, product complexity, and product unsustainability versus sustainable distributed manufacturing. There are three main findings from the research. First, technological advances enable expansion of sustainable distributed manufacturing of original products, if the products are small simple original products rather than large complicated original products. Second, technological advances enable sustainable distributed manufacturing of products that are more complex than could otherwise be made far from manufacturing infrastructures, but which nonetheless are not the most complex products. Third, technological advances enable more sustainable distributed production of products with unsustainable features, if technological advances are applied also to some existing distributions of manufacturing. Consideration of these three main findings and three further findings, suggests two complementary strategies for expanding sustainable manufacturing distributions: trade-off reduction and trade-off avoidance. Overall, the research is novel through its inclusion of diverse technologies and distributions of manufacturing in order to determine their relative potential to improve the production of physical goods at more diverse locations by more diverse people.

CONTENTS

List of Figures

ABBREVIATIONS

AR	Augmented reality
BoM	Bill of materials
CAD	Computer-aided design
CNC	Computer numerical control
DFMA	Design for manufacture and assembly
DIY	Do-It-Yourself
ETO	Engineer-to-order
ICT	Information and communication technologies
ITE	Information-theoretic entropy
MTF	Make-to-forecast
MTO	Make-to-order
S/CKD	Semi / Complete Knock-Down Kits
VSP	Virtual-social-physical

ORIGINAL PUBLICATIONS

The dissertation is based upon research and findings reported in the five scientific journal papers listed below.

I. Fox, S. (2014) Potential of virtual-social-physical convergence for project manufacturing. *Journal of Manufacturing Technology Management*, *25*(8), 1209-1223.

II. Fox, S. (2010) The importance of information and communication design for manual skills instruction with augmented reality. *Journal of Manufacturing Technology Management*, *21*(2), 188-205.

III. Fox, S. (2015) Moveable factories: how to enable sustainable widespread manufacturing by local people in regions without manufacturing skills and infrastructure. *Technology in Society*, *42*, 49-60.

IV. Fox, S. & Li, L. (2012) Expanding the scope of prosumption: a framework for analysing potential contributions from advances in materials technologies. *Technological Forecasting & Social Change*, *79*(4), 721-733.

V. Fox, S. & Alptekin, B. (2018) A taxonomy of manufacturing distributions and their comparative relations to sustainability. *Journal of Cleaner Production*, *172*, 1823-1834.

AUTHOR’S CONTRIBUTION

Paper I	Sole author. The author carried out all research and writing.
Paper II,	Sole author. The author carried out all research and writing.
Paper III	Sole author. The author carried out all research and writing.
Paper IV	Lead author. The author carried out all research and writing. The second author, Leijun Li provided verification of material science details.
Paper V	Lead author. All research was carried out by the author, other than research related to Turkey carried out by the second author Büşra Alptekin in the Turkish language, who at the time was an MSc exchange student working under the author’s supervision. The author carried out all writing.

1 INTRODUCTION

This section provides description of background to the research, research gaps, hypothesis, research questions, research methods, and structure of the dissertation.

1.1 Background

As summarized in **Figure 1**, the background of the research is the trend towards more inclusive manufacturing. This includes all levels of technologies, from basic to cutting-edge, to enable more diverse geographic and demographic distributions of manufacturing, which can improve ecological sustainability and social sustainability (NIAS, 2018; WMF, 2018).

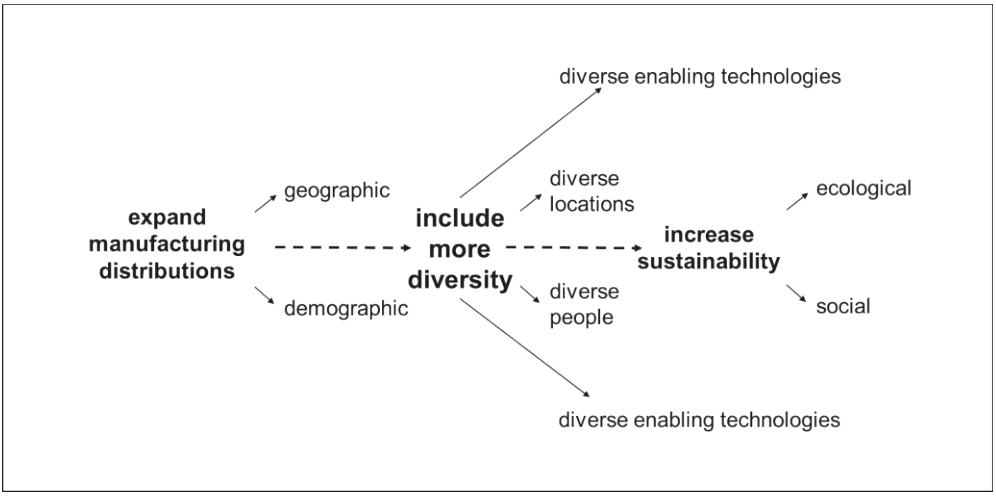


Figure 1. Inclusion of more diverse locations and people in manufacturing

Overall, sustainability is concerned with meeting the needs of the present without compromising the ability of future generations to meet their needs (Brundtland et al., 1987). The ecological sustainability of production is affected by what is inputted, how it is processed, and what is reused. It is possible that the ecological sustainability of manufacturing can be improved by expanding geographic distributions of manufacturing. For example, increasing the diversity of locations included in manufacturing, through re-shoring and redistribution, can reduce long-distance transportation of materials and goods (Ellram et al., 2013; Gray et al., 2017; Fratocchia et al., 2014; Jreissat et al., 2017). Social sustainability can be increased through equal opportunities to participate, community engagement and social ownership. It is possible that the social sustainability of manufacturing can be improved by expanding demographic distributions of manufacturing. For example, increasing the diversity of people included in manufacturing can contribute to growth of maker communities (Kohtala & Hyysalo, 2015; O'Sullivan, 2018; Stangler & Maxwell, 2012; Tanenbaum et al., 2013). Ecological sustainability and social sustainability are related to economic sustainability. Typically, economic sustainability depends upon sales, and the margin between the prices and the costs of what is sold. It is possible that sales can be increased and prices can be higher for products marketed on the basis of their sustainability (Jung & Jin, 2016) Also, it is possible that production costs can be reduced, for example, if individual customers act as prosumers by carrying out some of production themselves (Tian et al., 2017). However, increasing the individualization of products can increase production costs and times. Accordingly, companies need to charge higher prices or reduce individualization (Squire et al., 2006).

The topicality of expanding geographic and demographic manufacturing distributions to improve ecological and social sustainability is shown by the European Union's (EU) Manufuture Vision 2030 Report including the need for manufacturing to provide a robust foundation for ecologically and socially sustainable development of the EU (Manufuture High-Level Group, 2018). Also, China promotes wider geographical and social distribution of manufacturing through its "makerspaces for the people" policy. Like other countries such as Britain (Moreno & Charnley, 2016) and India (Mudambi et al., 2017), China aims to increase the variety of manufacturing enterprises through including the creative potential of diverse individuals at diverse geographical locations (Lindtner, 2015; Marshall and Rossi, 2017).

In the research reported here, manufacturing ranges from production of small bespoke consumer goods to large engineered-to-order capital goods. Also, as all production phases can affect originality, complexity and sustainability, manufacturing spans from materials extraction to product assembly. Technological advances have potential to expand the geographic distribution of manufacturing, which can introduce opportunities for improved ecological sustainability. For example, technological advances support wider geographic distribution of manufacturing by bringing about reductions in the number, size, weight and cost of machines needed in manufacturing. A well-known example is 3D printing. In addition, there are reductions in the sizes of machine tools (Brecher et al., 2010), and different manufacturing processes being combined in hybrid machines (Flynn et al., 2016). Also, technological advances have potential to expand the demographic distribution of manufacturing, which can introduce opportunities for improved social sustainability. For example, it has been argued that expansion of Internet coverage and Web-based platforms can enable a wider social distribution of manufacturing (Jiang et al., 2016).

However, many claims for enabling technologies and distributed manufacturing have characteristics of vague hype (Anderson, 2012; Finocchiaro, 2013). Consider, for example, the title of an article in the scientific journal nature: Make anything, anywhere (Mandavilli, 2006). Yet, those countries that dominated global manufacturing 10 years ago continue to dominate global manufacturing (Li, 2018), and manufacturing has contracted in many parts of the world (Rodrik, 2016). Meanwhile, some prosumption organizations in the DIY maker movement have contracted rather than expanded (Mac, 2016; Malone, 2017). Accordingly, research is needed to provide more specificity and balance in evaluation of the potential for technological advances to enable sustainable distributed manufacturing necessary for inclusive manufacturing (NIAS, 2018; WMF, 2018).

1.2 Research gaps

In this subsection, the three research gaps addressed in this dissertation are introduced. These research gaps are concerned with fundamental challenges that limit sustainable distributed manufacturing in many sectors. The research gaps are product originality, product complexity, and product unsustainability versus sustainable distributed manufacturing. The three gaps are analysed in more detail in section 2, Literature Review.

1.2.1 Product originality versus sustainable distributed manufacturing

An original product is a product that is designed and manufactured for the first time. If it is not made again, it is an original one-of-a-kind product. Examples of original one-of-a-kind products range from bespoke apparel to engineered-to-order (ETO) super yachts and spacecraft. Original products begin with the product concept ideas of individuals who want to have a product that is particular to their own special requirements. This is very different to products that are developed to meet the common requirements of millions of people, who are identified through market research as forming a market segment (Latter et al., 2010; Nam et al., 2010).

Within established manufacturing practices, making anything that can be imagined involves project manufacturing of original one-of-a-kind products by bespoke/engineer-to-order (ETO) organizations. Compared to mass production organizations that make standard goods to forecast (MTF) and mass customization organizations that make goods to order (MTO), project manufacturing bespoke production/ETO organizations tends to rely on more traditional subtractive manufacturing practices and more traditional manual skills. They rely on such practices and skills throughout iterations of work and rework, which are needed to transform each customer's individual idea into a completed original product (Haug et al., 2009).

Material wastage and production inefficiencies due to reliance on more traditional subtractive processes during iterations of work and rework limit potential to increase the ecological sustainability of bespoke/ETO production. Also, long manual skill training durations limit potential to expand the distribution of bespoke/ETO production (Anderson & Krathwohl, 2001; Bryson et al., 2018), and so limit potential to increase social sustainability by inclusion of more diverse people in bespoke/ETO production. Thus, expansion of making anything can be hindered by reliance on traditional subtractive practices and reliance on human manual skills. Here, it is important to note that hype claims for additive manufacturing related to anybody anywhere being able to 3D print anything overlook multiple limitations of 3D printing, such as limitations to the size and strength of 3D printed goods (Finocchiaro, 2012; Oropallo & Piegl, 2016). Hence, as is explained in more detail in the Literature Review section, a research gap is failure to take into account the trade-off of product originality versus sustainable distributed manufacturing.

1.2.2 Product complexity versus sustainable distributed manufacturing

Within established manufacturing practices, anything is not made anywhere. Rather, complex goods are made at particular locations where the necessary production resources are available (Felipe et al., 2012; Hartmann et al., 2017). Product complexity increases as the numbers increase of part types, interconnection types, interface types, product technologies and product functions. The complexity of products is relative. For example, a family car is a more complex product than a bicycle. This is because a family car comprises more part types, more interconnections types, and more interface types than a bicycle. Furthermore, it involves more technologies in provision of more functions. Moreover, there are exponentially more interdependencies between parts, interconnections, interfaces, technologies and functions (Dawidson et al. 2004; Pugh, 1991; Ulrich & Eppinger, 2000).

The manufacturing of complex products involves deployment of advanced production resources (Longo et al., 2017; Tsarouchi et al., 2017). Often, manufacturers who are already dominant in a particular manufacturing sector determine the countries and the locations within countries where complex products will be manufactured (Rodrik, 2016). The exact location in a country where production of complex products takes place is determined through analyses of multiple supply and demand factors. These analyses seek to take sustainability issues into account (Jokar & Sahraeian, 2012). However, the challenges of siting production facilities anywhere to increase ecological and social sustainability are largely overlooked in claims for distributed manufacturing (Gress & Kalafsky, 2015). Hence, as is explained in more detail in the Literature Review section, a research gap is failure to take into account the trade-off of product complexity versus sustainable distributed manufacturing.

1.2.3 Product unsustainability versus sustainable distributed manufacturing

Ecological sustainability of products can be increased, for example, by less wasteful use of finite materials. Social sustainability of product can be increased through, for example, widening opportunities to participate in manufacturing operations (Seuring & Müller, 2008). Claims that technological advances will enable anything to be made anywhere more sustainably (Kohtela, 2015; Mandavilli, 2006; Rauch et al., 2015) do not take into account that many products have unsustainable features such as their sales depending upon inclusion of finite natural resources or other unsustainable materials sourcing (Hoekstra & Wiedmann, 2014). Potential for improving the sustainability of manufacturing can be constrained by the unsustainability of the products that are to be made: especially if increasing volumes are to be made (Gould et al., 2015; Moir & Mowrer, 1995; Hoekstra, 2015).

Vague definitions of what is to be made by whom for what users at what use location lack the specificity needed to inform the engineering of sustainable production (Romli et al., 2015). Necessary specificity is often overlooked in claims for distributed manufacturing. Rather, vague claims are made that expanding the distribution of manufacturing will improve the sustainability of production. Such vagueness enables proponents to argue fallacies of single cause and incomplete evidence, which involve cherry picking particular aspects of special cases (Pohl, 2004). For example, goods made of one material that can often be locally sourced, such as furniture made of locally available renewable wood, are put forward to argue for increasing the distribution of manufacturing. However, goods often comprise many different materials, which can seldom be sourced locally, such as rare earths (Stegen, 2015). Hence, as is explained in more detail in the Literature Review section, a research gap is failure to take into account the trade-off of unsustainable product features versus sustainable distributed manufacturing.

1.3 Research hypothesis

The fundamental challenges of the three trade-offs described above limit expansion of distributed manufacturing that is sustainable. For example, irrespective of sector, making anything that can be imagined involves multiple waste-generating production iterations with traditional subtractive processes that involve manual skills, which are in short supply at many locations because they are skills that take years to master. Also irrespective of sector, making complex goods anywhere involves having advanced production facilities wherever anywhere may be. In addition, there is strong demand in many sectors for products that have unsustainable features. For example, the value of some luxury products depends upon them being manufactured in one particular country. This involves intercontinental inbound transportation of raw materials and intercontinental outbound transportation of completed goods. Consideration of the three fundamental trade-offs informs the following hypothesis:

> *the potential of technological advances to enable expansion of sustainable distributed manufacturing is limited by the originality, complexity and unsustainability of products.*

In particular, it can be anticipated that potential for expansion of sustainable distributed manufacturing will be highest when what is to be produced has low originality, low complexity and high sustainablity.

1.4 Research questions

As summarized in **Figure 2**, the research hypothesis is addressed through three research questions related to the five papers.

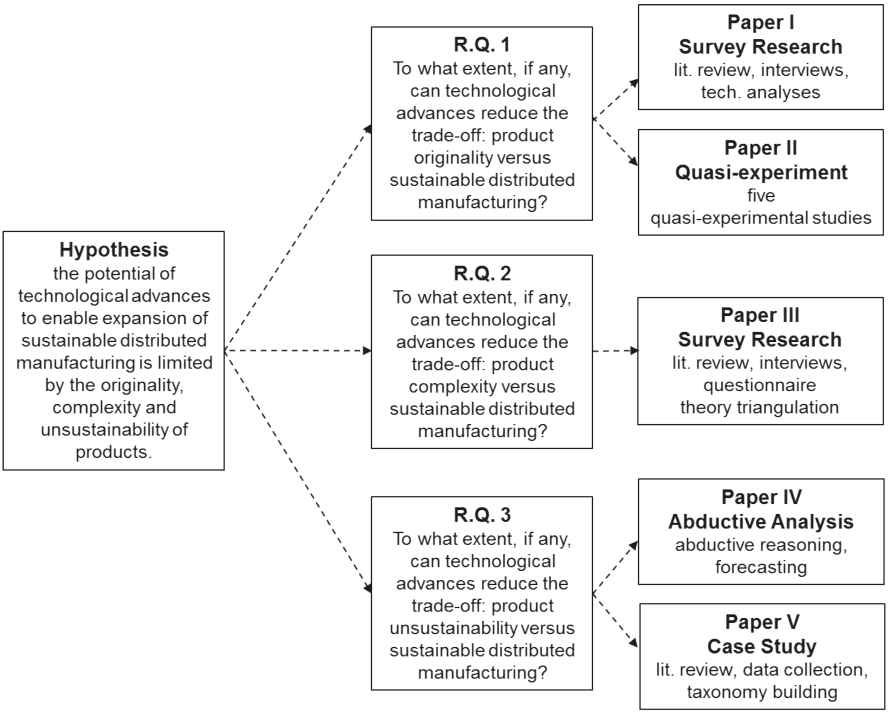


Figure 2. Research hypothesis, research questions, and research methods

R.Q.1 : To what extent, if any, can technological advances reduce the trade-off: product originality versus sustainable distributed manufacturing? (Papers I and II)

R.Q.2 : To what extent, if any, can technological advances reduce the trade-off: product complexity versus sustainable distributed manufacturing? (Paper III)

R.Q.3 : To what extent, if any, can technological advances reduce the trade-off: product unsustainability versus sustainable distributed manufacturing? (Papers VI and V)

The three research questions have significance for the wide range of parties that have interest in expanding distributions of manufacturing. For example, Research Question 1 addresses product originality, which is an important topic for those who advocate locating production closer to individual customers and their personal requirements (Moradlou & Backhouse, 2016). Research Question 2 addresses product complexity, which can be a principal determinant of where manufacturing can be carried out (Inman & Blumenfeld, 2014). Research Question 3 addresses product unsustainability, which is an important topic for all who are interested in expanding production of goods comprising finite materials (Yu et al., 2016).

Findings from addressing the three research questions can have impact for government policy makers considering whether to facilitate local manufacturing in order to generate local prosperity (Vanchan et al., 2018). Also, findings can have impact for manufacturing companies considering which aspects of their operations to locate at which locations (Brandon-Jones et al., 2017). In addition, findings can have impact for communities and individuals seeking to make goods for personal consumption and/or for sale to others (Kwon & Lee, 2017). Overall, impact from research question findings can come from addressing vague hype found in claims for expanding distributions of manufacturing (Anderson, 2012; Mandavilli, 2006). In particular, claims that ignore trade-offs between product originality, product complexity, product unsustainability and sustainable distributed manufacturing.

1.5 Research methods

1.5.1 Characteristics of the research questions

Research questions should be addressed through relevant research methods. In particular, research methods that match the characteristics of research questions.

Here, the research questions address the broad and oblique influence of the three fundamental trade-offs. With regard to breadth, the research questions address the potential for technological advances to reduce three fundamental trade-offs, which can exert constraining influence over manufacturing anything anywhere sustainably. As is appropriate in scientific enquiry (Fawcett & Downs, 1986), and as is appropriate in considering claims such as technological advances will enable anything to be made anywhere (Mandavilli, 2006), the research was intentionally inclusive of the diversity of manufacturing in order to facilitate identification of common underlying issues that transcend sectors and borders. For example, research into original one-of-a-kind products ranges from small bespoke consumer goods to large engineered-to-order (ETO) capital goods (Paper I). Also, research into manufacturing distributions ranges from subsistence do-it-yourself (DIY) to centralized industrial production in process plants (Paper V).

With regard to obliqueness, the three fundamental trade-offs are not seen easily because they are often latent variables, which only become manifest variables when production is positioned against the trade-offs. For example, as more authority over design and manufacturing is offered to more individual customers and/or as rare finite materials are included in products. However, the trade-offs may remain neither visible nor measurable when they become manifest. Rather, only consequences, such as increasing inefficiencies, may be recognized. This is different to potentially visible and measureable variables, such as potential tool wear, which become visible and measurable variables such as actual tool wear. Further obliqueness arises from the research being concerned with investigating potential from technological advances. Thus, the research questions are concerned with what could be done, rather than what already was done, to reduce the influence of latent variables that may not be visible and measurable even when they become manifest variables.

1.5.2 Improving upon the verisimilitude of extant explanations

Research into phenomena of such breadth and obliqueness has to go beyond quantitative methods that focus on the directly measurable effects of a directly measurable independent variable, such as tool wear, on a directly measurable dependent variable, such as cutting accuracy. Furthermore, in recent years, it has become apparent through meta-research studies that quantitative research does not ensure that published research findings will improve the description and explanation of complex phenomena. Rather, even results published from randomized control trials are often neither balanced nor useful (Ioannidis, 2018; 2016; 2005; Shun-Shin and Francis, 2013).

In the research reported in the five published scientific journal papers, research methods were not selected to enable gathering, quantification, and analysis of large volumes of data. Rather, qualitative methods were selected and applied to improve upon extant descriptions and explanations of potential for sustainable distributed manufacturing. In other words, to make scientific contributions by improving upon the verisimilitude of extant descriptions and explanations (Niiniluoto, 2014). This was done by applying qualitative research methods to investigate fundamental trade-offs. The usefulness of the research is indicated by consideration of the resultant scientific papers leading to the author being invited to the steering committee of India's Inclusive Manufacturing Forum, and cooperating with the Finnish Foreign Ministry's Finnpartnership programme.

1.5.3 Research methods

As summarized in Figure 2, and described in more detail in dissertation section 3, a range of qualitative research methods were applied including survey research, quasi-experiment, theory triangulation, abductive analysis, and case study. Recent years have seen considerable debate about the relative merits of different research methods, and it has come to be recognized that balance in the application of research methods is of the utmost importance to address potential biases in research and its publication (Ioannidis, 2018; 2016; 2005; Shun-Shin and Francis, 2013). Accordingly, application of all research methods encompassed positives and negatives.

Throughout the research, multivocal literature reviews were carried out. These are literature reviews that include grey literature as well as formal scientific literature (Bogdanski & Chang, 2005; Patton, 1991). Grey literature includes publicly available online information that may be produced by academia, business, communities, industry or government, which is not necessarily peer reviewed and controlled by commercial publishers. An example of grey literature is the 2018 Report of the World Manufacturing Forum (WMF, 2018). Grey literature is relevant because of two reasons. First, technological advances can involve fast moving trends, which are reported contemporaneously in online media. By contrast, although formal scientific literature is most important, it can be less up to date. Second, much of prosumption is reported online in blog reports etc.

As reported in dissertation sections 3.1 (Paper I) and 3.3 (Paper III) the informant style of unstructured interview was used. Hence, the author did not seek to control the interviews. Rather, interviewees freely expressed their thoughts and took the interviews in the direction that they chose. This type of unstructured interview can be contrasted with the respondent style of unstructured interview where the interviewer seeks to follow a more defined agenda (Powney & Watts, 1987). Interviewees were a purposive sample of participants knowledgeable in the particular topics of the research, and the informant style of unstructured interview was used to maximise the range of information, both positive and negative, that could be elicited from participants (Robson, 2011). This type of interview was applied because the interviews were concerned with what could be done with technological advances that were not yet widely applied. By contrast, structured interview techniques were not applied because they would have involved some presupposition of what was possible with the technological advances, and could have constrained the scope of expression by interviewees about future possibilities.

As reported in dissertation section 3.2 (Paper II), quasi-experiments were used to investigate the effects of information and communication design on the relative efficacy of different information and communication technology (ICT) options for manual skills instruction. Quasi-experiments differ from experiments by participants not being a random sample. Rather, participants are a purposive sample (Cook & Campbell, 1979). In this research, participants were a purposive sample of people whose work involves use of different ICTs. This was necessary to minimise potential for lack of familiarity with ICTs to confound effects. For example, lack of familiarity with ICTs could confound effects such as changed speed of manual assembly due to different information and communication designs for manual skills instruction (Pearl, 2009). In particular, without some familiarity with the ICTs, participants could suffer cognitive overload for work instructions irrespective of whatever information and communication design is applied (Chandler & Sweller, 1991).

Theory triangulation was applied in the research reported in Paper III. This involves applying different theoretical perspectives in the examination of a phenomenon. This is necessary because no single theory can have a monopoly on explanations. Rather, each theory has its unique strengths and weaknesses that reflect the partial worldviews of any who develop a theory. Hence, the combination of theories can yield a more complete picture of complex phenomena. In particular, the application of different theoretical perspectives can reveal areas of theoretical agreement and disagreement. Both should be taken into account to enabled balance analyses (Bhaskar, 1978; Modell, 2015). The three theories applied are Resource-Based Theory (RBT), Knowledge-Based View (KBV), and Transaction Cost Economics (TCE), which are applied widely in the analysis of production, including the distribution of manufacturing (Fratocchi et al., 2016).

As reported in dissertation section 3.4 (Paper IV) abductive analyses concerned with advances in materials technology were carried out. Abductive analyses involve iterative cycles of reference to theories and observations to increase understanding of causation. By contrast, inductive reasoning involves moving from observation to theory; and deductive reasoning involves moving from theory to observation (Josephson & Joshephson, 2007; Paavola, 2004). Accordingly, the abductive analyses involved reference to materials science theory and observations of developments in manufacturing brought about by advances in materials technologies.

As reported in dissertation section 3.5 (Paper V), an applied research case study was carried out. This type of case study is used to exemplify a general topic, while specifying general concepts with practical examples, and can involve comparison of several alternative options within the same case (Yin, 2011). Case study involved multi-vocal literature review and gathering of information face-to-face and by email. The research concluded in the formulation of a taxonomy of manufacturing distributions and their comparative relations to sustainability. The taxonomy building drew upon, but went beyond, previous manufacturing taxonomies by others (Miller & Roth, 1994; Zhao et al., 2006).

Thus, multimethod qualitative research was carried out in order to improve upon previous explanations about potential for expanding sustainable distributed manufacturing.

1.6 Structure of dissertation

Section 2: Literature Review. Review of the literature concerned with each of the three research gaps is provided in terms of the three fundamental trade-offs: product originality, product complexity, and product unsustainability versus sustainable distributed manufacturing.

Section 3: Results. The contribution of each of the five journal papers to addressing the research questions is explained with text and diagrams. In particular, Papers I and II address Research Question 1. Paper III address Research Question 2. Papers IV and V address Research Question 3.

Section 4: Discussion. Research findings are related to the research questions; the principal finding is stated and related to the research hypothesis; limitations and generalizability are discussed together with examples from each of the five papers; contributions to theory and for practice are described.

Section 5: Conclusions. A statement of main contributions and supplementary contributions is provided. Then, directions for further research are proposed in terms of two strategies in the context of inclusive manufacturing.

2 LITERATURE REVIEW

In this section, a review of the literature concerned with the research gaps is provided as follows: product originality, product complexity and product unsustainability versus sustainable distributed manufacturing.

2.1 Product originality versus sustainable distributed manufacturing

Within established manufacturing practices, making anything that can be imagined involves project manufacturing of original one-of-a-kind goods by bespoke/ETO production organizations. The term project manufacturing encompasses hand-made bespoke production of clothes, jewellery, etc., and ETO production of ships, spacecraft, etc. Specialist parts for project-manufactured products can involve both bespoke and engineer-to-order (Hayes & Wheelwright, 1979; Norton, 2006; Vonderembse & White, 2007).

Whether bespoke/ETO production original goods are small or large, they begin as a rough concept in the mind of an individual customer and progress through multiple iterations of concept design, detail design, and various stages of production to completion. Thus, when project manufacturing begins with the nascent concept of an individual customer, it can be considered as bespoke/ETO production. Bespoke/ETO production differs from the make-to-forecast (MTF) of mass production and the make-to-order (MTO) of mass customization. In particular, MTF and MTO can be based on the common requirements of many thousands of customers, and have different customer order decoupling points (CODP) to bespoke/ETO (Willner et al., 2016). In particular, concept-to-order project manufacturing is tied to a specific customer order before the product concept is defined fully. By contrast, MTO is tied to a specific customer order when the customer selects from product configuration options: for example, configuration options for a family car. MTF is tied to a specific customer order, such as from an electrical retailer selling vacuum cleaners, after production is completed (Olhager, 2003; Wikner & Rudberg, 2005).

Bespoke/ETO production organizations cannot easily implement technological advances that have reduced materials wastage and training durations in MTF and MTO. Rather, bespoke/ETO production organizations continue to rely on traditional subtractive manufacturing processes and human manual skills throughout the multiple iterations of work and rework, which are needed to transform each customer's individual idea into a completed original product (Korpivaara et al, 2014; Sjøbakk et al., 2014). This is because compared to MTF and MTO, ETO project manufacturing of original products is much more unpredictable. This is due to individual customers having authority over product design and manufacture (Tu, 1997; Yang, 2013).

Importantly, individual customers do not necessarily know exactly what they want at the outset. Rather, customers can have vague ideas that evolve through multiple iterations of design and manufacture. Accordingly, product specifications are unpredictable. By contrast, manufacturers of mass produced MTF products, such as vacuum cleaners, know the forms, functions and finishes of all products and their components before any orders are received. Also, manufacturers of mass custom MTO products, such as cars, know the forms, functions and finishes of their products and component configuration options for their products before any orders are received (Agrawal et al., 2002; Haug et al., 2009).

Then, unlike MTF and MTO producers, the scheduling of bespoke/ETO production activities has to be changed in response to the changing priorities of individual customers (Rahim & Baksh, 2003). Indeed, the authority offered to individual customers for project manufacture can result in there being design certainty only after production has been completed. Moreover, there can be little, or no, repetition of post-production design certainty. A spacecraft, for example, which is project manufactured for individual customers can be mission-specific and its design may never be used again (Williamson, 2003).

The unpredictability of product and component specifications introduced by offering authority to individual customers causes unpredictability throughout operations. For example, the development of bills of materials (BoM) and efficient deployment of computerised production planning systems is not technically feasible when there is only post-production design certainty. Furthermore, the development of BoM and deployment of computerised production planning systems is not economically viable when there is little, or no, repetition of post-production design certainty. Accordingly, original drawings, estimates, purchase orders and works orders are prepared and checked for each order in project manufacturing. Having to generate original production data for each order makes it extremely difficult to identify opportunities for batch manufacturing. Hence, production optimization can be haphazard across the whole of the project manufacturing (Cutler, 2005; Elgh, 2012; Korpivaara et al., 2014; Little et al., 2000).

Moreover, offering authority over design and manufacture to individual customers leads to the propagation of unpredictability and consequent inefficiencies throughout manufacturing activities. For example, unpredictability can be introduced into components when individual customers are offered authority. This is because each individual customer can introduce previously unknown suppliers and influence the location of production (Gosling and Naim, 2009). More generally, human operated manual subtractive processes such as cutting and grinding persist in the bespoke/ETO production of original one-of-a-kind components and products: with few opportunities for automation (Korpivaara et al., 2014; Sjøbakk et al. 2014). By contrast, much of wasteful traditional subtractive manufacturing has been eliminated from MTF and MTO production by the consolidation of many separately made small parts into a few single-piece sub-assemblies and assemblies produced with, for example, molds and presses. This consolidation is technically feasible and economically viable in MTF and MTO because, unlike in bespoke/ETO production there is high predictability and high repetition of sub-assemblies and assemblies in MTF and MTO products (Boothroyd et al., 2002; Yang et al., 2019).

So it is that making anything that can be imagined continues to involve traditional wasteful subtractive work and rework. Also, there is continuing dependence on human manual skills, which can take many years to acquire through conventional training practices and are often in short supply (Giffi et al., 2018; Yizengaw, 2018). Overall, reliance on traditional wasteful iterations and human manual skills limits potential for expansion of sustainable distributed manufacturing of original one-of-a-kind goods. Here, it is important to note that hype claims for additive manufacturing related to anybody anywhere being able to 3D print anything overlook multiple limitations of 3D printing, such as limitations to the size and strength of 3D printed goods (Finocchiaro, 2012; Oropallo & Piegl, 2016).

With regard to **Research Question 1, to what extent, if any, can technological advances reduce the trade-off: product originality versus sustainable distributed manufacturing?**, it is important to note that challenges involved in manufacturing original products are often addressed by bespoke/ETO production companies trying to reduce individual customer authority over design and manufacture. In particular, bespoke/ETO production companies try to move towards MTO, which reduces their reliance on traditional wasteful iterations and their reliance on scarce human manual skills needed to transform a customer's idea into a completed product (Christensen & Brunoe, 2018; Haug et al., 2009). However, scope for product originality cannot be reduced if anything that can be imagined is to be made anywhere (Mandavilli, 2006). Rather, **technological advances need to facilitate wherever required: reduced wasteful production iterations and improved provision of scarce manual skill knowledge, without compromising potential for product originality.**

2.2 Product complexity versus sustainable distributed manufacturing

Within established manufacturing practices, anything is not made anywhere. Rather, a few countries have global dominance in manufacturing complex products (Felipe et al, 2012; Hartmann et al., 2017; Hidalgo & Hausmann, 2009; Hidalgo et al., 2007). Hence, other countries that try to set up production of complex products have to compete against established countries, which have formidable head starts in both production excellence and global reach. Global manufacturing led by a few dominant countries is facilitated by the development of digital and physical infrastructures that reduce the time and cost of transactions and transportation (Berg et al., 2017). This enables time and cost competitive production for an entire geographic region to be centred in one hub location. For example, China is investing in Ethiopia as a base for Chinese manufacturing for the markets of many African countries. Thus, globally dominant industrial producers can decide where industrial production is located and where it is not located (Rodrik, 2016; Pilling, 2017).

However, countries are no longer selected as new manufacturing hubs just because they have a supply of low cost human labour. This is because increased automation and digitalization reduce dependency on cheap labour, even in sectors that have previously been difficult to automate such as apparel manufacturing (Stacey & Nicolaou, 2017). This is a challenge for countries that are already trying to increase manufacturing by providing low cost labour to global producers. This is because there will be more factory work carried out by robots (Ayentimi & Burgess, 2018; Frey, 2015; Grabowski, 2017; Millington, 2017).

It is an even bigger challenge for countries that seek to be new providers of low cost labour to global manufacturers. It is an even bigger challenge because when highly efficient automation can enable industrial production more cost-effectively than people can produce anywhere, global manufacturers have less need to locate production where there are cheaper labour costs. Moreover, countries that are chosen to be manufacturing locations cannot be confident that they will remain production locations. Rather, countries can be rewarded quickly with some manufacturing jobs (Oqubay, 2015). However, these can be lost easily as global producers move their factories to be closer to new markets, back to their home country or move their factories to another foreign country of greater strategic significance to their home country (Baldwin, 2013).

Thus, rather than manufacturing being carried out anywhere, already globally dominant manufacturers in each production sector often decide where manufacturing will be carried out. They can decide where production will be located. Then, if they wish to do so, they can chose to automate production or move production somewhere else. This leaves the countries that host their production with little choice but to accept reduced human employment through automation. Indeed, extensive research by others has led to identification of three major trends in manufacturing (Amirapu & Subramania, 2014; Dasgupta & Singh, 2006; Desilver, 2017; Rodrik, 2016; 2014; 2013). The first scenario is that already industrialized high-income countries suffer falls in human factory jobs but can maintain factory output if there is major investment in factory innovation, such as autonomous robot workers. Also, continued manufacturing operations could lead to continuation of manufacturing-related services. The second scenario is low-income countries, which have a head start in factory production, increase output and possibly human jobs - if they have access to sufficient digital and physical infrastructure for them to be regional manufacturing hubs. The third scenario is low-income countries without a head start in factory jobs suffer a decline in both factory output and factory jobs. Thus, rather than manufacturing being carried out anywhere, there is ongoing reduction in manufacturing in many parts of the world (Amirapu & Subramania, 2014; Dasgupta and Singh, 2006; Desilver, 2017; Rodrik, 2016; 2014; 2013).

From the point-of-view of individuals and communities, DIY manufacturing of more complex products by applying technological advances such as open source hardware and 3D printing (Powell, 2012) has yet to counteract the concentration of established manufacturing. Indeed, prominent organizations in the maker movement have contracted rather than expanded (Mac, 2016; Malone, 2017). Furthermore, although it is argued that the maker movement can boost urban economic development, doing so depends on an ecosystems of existing companies to provide materials, components and tools (Wolf-Powers et al, 2017).

More broadly, much of DIY manufacturing involves physical goods and related systems produced within conventional manufacturing. For example, Wi-Fi-enabled bulbs are offered by a global physical mass production company. Around these offerings, DIY communities evolve as individuals share hacks online concerned with how to better imagine and engineer more complex lighting scenes. This leads to word-of-mouth marketing for the MTF and MTO companies' offerings (McCole, 2016). Similarly, ikeahackers.net is a Website for individuals who make their own original unique modifications and re-purposing of Ikea products. Ikeahackers.net is not supported or endorsed by Ikea. Nonetheless, Ikea gains from Ikeahacker.net through new positive examples of the potential of its products (Picard, 2016). Meanwhile, there is global expansion of established less complex DIY, such as home assembly of flat-packed cupboards, through the expansion of companies such as Bauhaus and IKEA into new geographical territories. Such DIY involves home assembly of product kits that have been made to forecast (MTF) through established manufacturing practices (Daunfeldt et al., 2017).

With regard to **Research Question 2, to what extent, if any, can technological advances reduce the trade-off: product complexity versus sustainable distributed manufacturing?**, it is important to note that few countries in recent decades have been successful in transitioning from being producers of simple products, such as basic commodities with minimal processing, to being producers of complex products. Rather, there is increasing "unbundling" of global manufacturing value chains. In previous decades, the development of a manufacturing base involved building capabilities along the whole of manufacturing value chains. Countries that did this, such as Japan and South Korea, developed complex manufacturing infrastructures. By contrast, the "unbundling" of global industrial value chains does not involve organic development of capabilities along the whole of manufacturing value chains. Rather, it involves opening up cheap local manufacturing sites to global manufacturers (Baldwin, 2013). Thus, if anything is to be made anywhere, **technological advances need to facilitate the ecologically and socially sustainable provision of production resources for complex products**. Especially in locations

2.3 Product unsustainability versus sustainable distributed manufacturing

Claims that technological advances that enable anything to be made anywhere will increase the sustainably of production (Kohtela, 2015; Rauch et al., 2015) do not take into account that many products have unsustainable features. For example, sales of many products depend on functions and/or finishes that require finite natural resources and/or the transportation of natural resources from one side of the world to the other (Hoekstra & Wiedmann, 2014). For example, electric vehicles may come to reduce polluting emissions in the transportation of raw materials and completed goods in manufacturing value chains, but production of electric vehicles themselves depends upon the global transportation of rare earths and finite natural resources such as cobalt (Barteková & Kemp, 2016; Stegen, 2015).

Furthermore, despite claims about wider distributions of manufacturing being more sustainable, for example because they can be geographically closer to sources of supply and/or demand, there is already wide distribution of production operations that are less sustainable in some ways than more centralized alternative. For example, artisanal distributed manufacturing is well established throughout the world. This involves production of components and goods using artisan skills. Since the start of the new Millennium, some artisanal production has combined Web shops for global sales with traditional artisanal production from one location. More traditionally, manufacturing and sales are combined within one building, such as tailors' shops. However, artisanal production from raw materials to completed goods can be less sustainable than more centralized production because of the comparative difficulty of bringing ecological and social regulations to highly distributed production operations (Maconachie & Hilson, 2011; Seccatore et al., 2014).

For example, artisanal cobalt operations can provide more starting locations for highly distributed manufacturing than a few large-scale for-profit multinational operations. However, both involve sustainability challenges. On the one hand, large-scale operations can be regulated and taxed by government more easily than many artisanal operations. However, huge financial taxes paid for natural resource rights leads to governments being financially autonomous from citizens and, as a consequence, less responsive to citizens' needs for public services such as sanitation and education (Omeje, 2008). On the other hand, it has been argued that the government would be more likely to make decisions in the interests of local people if a larger proportion of cobalt is sourced through artisanal production by local people. Yet, artisanal operations by local people have been linked to human rights violations, including child labour and worker exploitation. Thus, both distributions involve serious challenges for social sustainability (Zeuner, 2018).

Also, both illustrate a general challenge for the social sustainability of manufacturing in the future. In particular, large-scale operations in raw materials processing can be automated to achieve the positive social outcome of reducing health and safety risks to human workers. However, this can have the negative social outcome of radically reducing human employment (Grossman, 2017). Meanwhile,

while both large-scale centralized and small-scale artisanal involve the ecological sustainability issue of extracting finite resources from the lithosphere that causes more disruption to the biosphere as materials are transported around the world (Zalasiewicz et al, 2017).

Moreover, sales of many other products depend upon attributes that involve serious sustainability issues. For example, thousands of tonnes of Moreno wool are transported from New Zealand to Italy for the manufacture of textiles that are then exported around the world, including back into the southern hemisphere (Mitchell et al., 2009). Customers buy the apparel made from these transcontinental textiles specifically because their authenticity and integrity. Authenticity refers to certainty that production was carried out at a certain location using local resources by local people: i.e. certainty that what is bought is not a counterfeit made somewhere else. Integrity refers to what has been made not being affected by coming into contact with anything that would reduce its authenticity (Beverland et al., 2009). Thus, while different distributions of Italian textile and apparel manufacturers, from corporations with large factories to family artisanal workshops, may strive to improve the sustainability of their operations, sales of their products are dependent upon global transportation that has negative ecological impacts (Resta et al., 2014).

It may be possible for some negative ecological impacts to be addressed by reducing carbon emissions (Riti et al., 2017; Yang et al., 2017) and making greater use of renewable energy (Juknys et al., 2014; Kahia et al., 2017). Furthermore, others have argued that growth of production enabled by technological advances can be "green" growth provided that regulations are introduced that drive technological innovation to increase ecological sustainability (Guo et al, 2017). By contrast, others have called into question whether it is possible for production growth to be "green" growth. The challenge being that technological advances, in addition to any improvements that they may bring, can be "means" that drive the unsustainable "end" of ever-increasing cumulative consumption (Gazhli et al. 2016; Lyon & Montgomery, 2015; Spangenberg, 2010).

Concerns about technological advances being the "means" that enable the "end" of unsustainable cumulative consumption (Gould et al., 2015; Hoekstra & Wiedmann, 2014) are as relevant to individuals and communities interested in DIY manufacturing as it is to governments and companies interested in reshoring manufacturing. For example, sustainability claims for Internet-enabled manufacturing include reducing the transportation of physical goods with the flow of digital data (Meyerson, 2015). However, potential negative consequences are often ignored, such as the massive carbon emissions that arise from the long distance formulation, transmission, and storage of increased digital manufacturing data (Schmidt, 2010; Xu, 2012). Similarly, Web-based distributed artisanal production has the advantage of breaking down traditional barriers to individuals being able to access goods designed in other countries and cultures, such as apparel made in Nepal via a Web platform set-up in Britain. However, it has the ecological disadvantage of extensive postage of physical goods across far distances. Moreover, the overall lower price of artisanal goods made in countries such as Nepal can drive up overall consumption (Smith, 2009).

With regard to **Research Question 3, to what extent, if any, can technological advances reduce the trade-off: product unsustainability versus sustainable distributed manufacturing?**, it is important to note that materials are transported around the world to enable production because there are few, if any, locations in the world that have the necessary materials in-situ to enable production of anything anywhere. Moreover, there are already wide distributions of manufacturing, such as artisanal production from raw materials to completed goods that are less sustainable in some ways than more centralized alternatives for production. Thus, if making anything anywhere is to be more ecologically and socially sustainable than current manufacturing, technological advances need to facilitate more sustainable material utilization across manufacturing distributions ranging from small-scale local distributed operations to large-scale centralized operations.

3 RESULTS

In this section, main results from the five papers are presented in the order of the research questions. Much more detailed information is provided in text, tables, figures and references in the five papers themselves.

3.1 Product originality versus sustainable distributed manufacturing (Papers I and II)

As explained in section 2.1., with regard to Research Question 1, *to what extent, if any, can technological advances reduce the trade-off: product originality versus sustainable distributed manufacturing?*, technological advances need to facilitate wherever needed, without compromising potential for product originality: reduction of wasteful production iterations and the provision of scarce skill knowledge required in production of original products

3.1.1 Potential for technological advances to reduce wasteful production iterations without compromising potential for product originality (Paper I)

Research Method

In Paper I, which is published in the Journal of Manufacturing Technology Management, findings are reported from literature review and unstructured interviews with ten experts. The informant style of unstructured interview was used. Hence, the author did not seek to control the interviews. Rather, interviewees freely expressed their thoughts and took the interviews in the direction that they chose. This type of unstructured interview can be contrasted with the respondent style of unstructured interview where the interviewer seeks to follow a more defined agenda. The interviewees comprised a purposive sample of technology experts. The interviews covered the technological state-of-the-art related to project manufacturing, and potential for future progress beyond the state-of-the-art. During interviews, technology demonstrations and manufacturing samples were provided by the interviewees. The information about technologies provided by interviewees was subsequently related to stages of project manufacturing: data capture, data conversion, design, manufacture, and assembly. For example, data capture in project manufacturing can often involve manual one-dimensional measurements that have to be converted into three-dimensional representations.

The potential of technologies to improve upon this was apparent from the information provided. For example, experts demonstrated the potential of digital cameras and digital scanners to capture data in three dimensions. Findings from interviews are reported in the analysis of how convergence between virtual, social and physical technologies (VSP) can address barriers to expansion and in the description of challenges for implementation. Literature review encompassed project manufacturing; technological convergence; and VSP convergence. Literature review addressed technical issues, micro-economic level issues, and macro-economic level issues related to the potential of VSP convergence for project manufacturing.

Main Findings

As summarized in Figure 3 and Table II of Paper I, one finding is that VSP convergence does introduce new opportunities to reduce wasteful production iterations without compromising potential for product originality. For example, new DIY companies have brought together three-dimensional (3D) solid modelling software (virtual), Web 2.0 functionality of the Internet in form of blogs plus links to Facebook, Twitter, YouTube (social), and digitally-driven manufacturing (physical) (Dahl, 2012). This VSP convergence extends to the simplification of project manufacturing of original goods with unique micro-electronic functionality. For example, micro-electronics board (physical), Web 2.0 functionality of the Internet in form of blog, forum, wiki plus links to Twitter (social), and micro-electronics programming (virtual).

In addition, there are other technologies that project manufacturing can implement to increase VSP convergence and reduce barriers to expansion. For example, digital photographs, digital videos, and digital scans can be automatically converted into three dimensional virtual models through photogrammetry software. These virtual technologies for data capture and data conversion can radically reduce reliance on arcane practices, which are still used to prepare three-dimensional (3D) drawings from sets of one-dimensional (1D) measurements made with tape measures, vernier gauges, etc. They can also reduce reliance on tasks that are traditionally needed to convert drawings into alpha numeric data for production operations. This is important as many project produced goods are needed to interface with existing goods and environments: for example, to enable refurbishment of machinery. Also, project produced goods, such as assistive devices are needed to interface with the unique and complicated measurements of the human body.

Furthermore, there are many new virtual technologies that reduce reliance on CAD skills to represent an idea for an original good as a digital design. For example, rough approximations of a form imagined in the mind's eye, such as physical models shaped from paper, card, etc., can be scanned and converted into 3D virtual models. Also, digital pens enable rough sketches to be drawn on paper and other surfaces to be rapidly converted into digital computer models. Moreover, many new CAD tools have intuitive user interfaces that are specifically developed for use by people without design training. Then, if project manufacturing should involve a large number of people and should be consistent with the aesthetic preferences of local cultures, languages of design can be formulated by user communities. This extends the read/write functionality of Web 2.0 from social authoring of text, in for example wikis, to social authority of designs for physical goods. Languages of design can be linked to criteria and processes for production and assembly.

Generative computation can be applied to languages of design. Generative computation automates the evolution of an infinite variety of designs. Generative computations can emulate what human designers/engineers do when they draw, erase, modify and/or move shapes such as lines and curves. With regard to the assembly of manufactured components, generative computations can enable designs to be produced in different sizes using different types of equipment – from the same file. First, this offers the possibility of manufacturing scale models for the purpose of learning how to put the components together to make the full-sized goods. Second, full-sized components can then be produced for assembly into full-sized goods. Also, the components produced for both the scale model and the complete good can have accurate friction-fit/snap-fit joints, which can be numbered to aid matching. Thus, the need for prior skill knowledge of assembly work can be reduced.

Overall, the combination of virtual, social, and physical technologies throughout production can enable reductions in times and costs. This can be achieved by replacing slow and expensive time-consuming labour-intensive traditional practices with faster and less expensive digitally-driven technologies. This includes the introduction of low cost and high performance manufacturing equipment by equipment developers / vendors, such as MakerBot, Mebotics, and ShopBot.

Thus, VSP convergence does have potential to reduce wasteful production iterations without compromising potential for product originality. However, as summarized in Table I of Paper I on its page numbered 1219, another finding is that the potential of VSP to reduce wasteful production iterations is limited for established bespoke/ETO organizations. In particular, VSP convergence is best suited to enabling expansion of project manufacturing of bespoke goods comprising few components. This is because they are well-suited to digital manufacturing with technologies such as scanners to capture measurements, photogrammetry, simple CAD tools, and digitally-driven manufacturing. In addition, inviting potential customers to formulate languages of design could expand customer base. Overall, the reductions to time and cost offered by VSP convergence can make bespoke consumer goods much more competitive with MTF mass produced and MTO mass custom goods.

Yet, although VSP convergence can enable project manufacturing firms to lower prices, it may be counterproductive for them to do so within their established brand identities. Consider, for example, bespoke businesses that are based at exclusive locations and offer project manufacturing of exclusive goods. Such bespoke businesses can have spent many decades developing their exclusive brand identities, and risk brand dilution if they introduce technologies that are not consistent with that brand identity. For example, brand exclusivity can limit the relevance of the read-write functionality of social media. Hence, exclusive bespoke businesses deploy the Internet for read-only and for customer transactions. Furthermore, traditional iterations of face-to-face dialogues, measurements, fitting and fixings are essential elements of their exclusiveness. Accordingly, the introduction of body scanners, generative computation, digitally-driven manufacturing etc., could undermine an exclusive brand identity.

For large ETO good's, there are major barriers to reducing wasteful production iterations with VSP. For example, large ETO goods can have large structural frameworks of heavy steel sections, which have to be put together from temporary structures such as scaffolding. Hence compared to small bespoke goods, large ETO structures are less suited to, for example, additive manufacturing machines and computer-numerically controlled (CNC) milling machines. Furthermore, large ETO structures, such as ocean-going ships, can be subject to extreme dynamic forces, and structural failures can lead to fatal accidents. Thus, although ETO goods can have potentially large communities with interest in the forms and finishes of design, it may not be possible to involve them in, for example, the social authoring of languages of design due to legal ramifications.

On the other hand, the knowledge sharing and knowledge evolution offered by Web 2.0 and associated social media could facilitate consensus building among stakeholder groups during detailed design, and later phases of the manufacturing process: especially if supported with virtual and physical models. Such applications of **VSP convergence, however, may have little potential to bring about major reductions in overall times and costs that could increase demand and enable expansion of large-scale ETO manufacturing**. **Rather, the greatest potential for VSP is in DIY manufacturing of small bespoke goods by individuals and communities who do not have the risks facing established bespoke manufacturers such as brand dilution**. Thus, as summarized in **Figure 3** below, there is limited potential to reduce material wastage and production inefficiencies due to continuing reliance on iterations of work/rework with traditional subtractive processes that limit potential to increase ecological sustainability of project manufacturing.

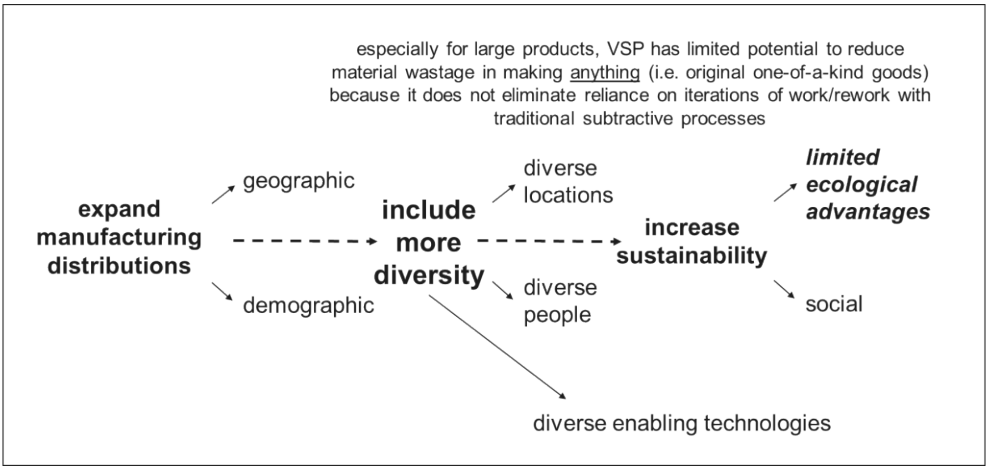


Figure 3. Material wastage in work/rework limits ecological sustainability.

3.1.2 Potential for technological advances to facilitate the provision of scarce manual skills knowledge wherever needed (Paper II)

Research Method

In Paper II, which is published in the Journal of Manufacturing Technology Management, findings are reported from five sequential quasi-experimental studies with 92 participants, which were concerned with instruction of manual skills with different technologies. All five studies involved two groups of participants. In all of the studies, one group of the two groups used Augmented Reality (AR) instructions. Augmented Reality (AR) is intended to enhance users' perceptions of the real world by showing additional information such as graphics and/or text. This additional information can be viewed in-situ, at the same time as the real world, via a variety of media including computer monitor, laptop screen, mobile telephone screen, and head mounted display. AR has potential to be applied in many types of production including bespoke/ETO production.

As shown in Figure 1 and Table II of Paper II on its page numbered 196, in all five studies, the other of the two groups used instructions comprising colour graphics prepared by virtual reality (VR) programmers. For brevity, these instructions are referred to here as VR graphics. Both types of instructions provide information about how to assemble the same wooden puzzle comprising the same six wooden pieces and square wooden box. Assembly involves putting each wooden piece in its correct position and sequence in a square wooden box with an open top. In all of the studies, each participant selected and positioned the physical wooden pieces when following the AR or VR graphics. Each participant worked individually and took part in only one study. Each group comprised an equal number of female and male participants. The participants were not a random sample. Rather, a purposive sample was obtained of professional people whose work involves the use of advanced information and communication technologies (ICT).

In the first three studies, the AR instructions were viewed via a 19 inch computer monitor, while the VR graphics instructions were printed out and viewed via six separate pieces of paper which were held in a lever arch file. In the final two studies, both AR instructions and VR instructions were viewed via a 14 inch laptop screen. Each participant was free to arrange the set-up of the options themselves to suit their own particular characteristics. The studies were not fully defined at the outset. Rather, studies evolved based on observations of the preceding study. In particular, observations enabled deeper analyses of the assembly task, and of the information and communication design for the application of the ICTs. These analyses prompted revision of instructions for each following study. Further information about each of the studies is provided in next five sub-sections.

Main Findings

Study One. Participants were asked to follow the instructions, but they were not asked to subsequently assemble the puzzle without instructions. All of the attempts to assemble the puzzle were successful. Following the AR instructions via the computer monitor took, on average, more than three times longer than following the instructions on paper. In this first study, as in the second and third studies, the six steps in the AR instructions were moved forward or backwards by pressing the arrow keys on a conventional keyboard. Participants were observed to be very methodical in their use of the AR instructions. By contrast, participants appeared to turn the pages of the printed VR graphics as quickly as possible.

Study Two. Participants were asked to follow the instructions. At the same time, they were told that they would subsequently assemble the same puzzle without instructions. They were also told that the purpose of following the instructions was to learn how to assemble the puzzle without instructions. Participants assembled the puzzle without instructions immediately after having completed the assembly once by following the instructions. Interestingly, the time taken to follow the VR instruction printed onto paper was much longer than in Study 1, because participants turned the pages much more slowly after looking much more carefully at the graphics. In this study, 80 percent of the people following the VR instructions were subsequently able to assemble the puzzle. By contrast, only 30 percent of people who followed AR instructions were subsequently able to assemble the puzzle. Also, average time taken for subsequent assembly by participants who had followed AR instructions was more than three times longer than the average time taken by participants who had followed VR instructions. One participant remarked: "the AR instructions were OK for identifying the piece but not for seeing where to put the pieces in the box".

Study Three. It was observed that most assembly difficulties in Study 2 involved the positioning of the first two pieces. In Study 3, all participants were asked to pay particular attention to the shapes and position of the first two pieces. This was the only difference in the instructions between Studies 2 and 3. The time taken to follow both AR and VR graphics instructions decreased by about a quarter. Also, the time taken to subsequently assemble after following AR instructions was more than halved. Furthermore, the percentage of successful completions was 90 for both groups. Interestingly, one of the participants who failed to complete the assembly remarked: "the AR is too exciting to remember".

Study Four. The instructions for Study 4 were the same as for Study 3, other than both AR instructions and VR graphics instructions were viewed via a 14 inch laptop. The VR graphics were presented as a presentation comprising six slides. Participants were able to move from one slide to another by pressing arrow keys on the laptop. AR instructions were also moved forward or backwards using arrow keys on the laptop. Thus, both groups now viewed and operated their respective instructions in the same way. In this study, the average time taken to follow AR instructions was closest to the average time taken to follow VR graphics instructions. Also, there was little difference between the two group's percentages of successful completions. One participant remarked that: "the inclination of the laptop screen is important to getting a good visualization".

Study Five. It was observed that the most of the assembly difficulties in Studies 3 and 4 arose from participants being uncertain as to the orientation of the first wooden piece on its Y axis. If the first piece is not orientated correctly, the second piece cannot be positioned correctly. In an effort to overcome this problem, the AR instructions were reprogrammed so that what had been the second piece was now instructed to be selected and positioned first. Similarly, the sequence of the VR graphics instructions was also re-ordered. This attempt to correct an observed assembly problem created another assembly problem. In particular, participants were observed to have difficulties in positioning the new first piece. These difficulties were observed to be more challenging among the participants following the AR instructions. One of these participants remarked that: "it would be better if the edges of the shapes were in black line". Another participant following the AR instructions remarked: "the edges of the shapes were not clear enough". None of the participants in the previous four studies had made any remarks about the edges of the shapes. This may have been because the new first piece was not the full length of the square open box into which the puzzle pieces are placed. By contrast, all of the other pieces are the full length. All of the durations were longer in Study 5 than in Study 4.

Studies 1 to 5: **Different information and communication technologies (ICT) have different strengths and weakness, which can be mediated by the design of information and its communication**. For example, AR information has potential to be more easily understood by more people because it presents additional instructional information in the same view as the real world. However, AR information can overlay key information in the real world and, as a result, reduce clarity. Yet, this overlaying of key information in the real world may only be counterproductive when information is configured in a particular way. A strength of instructions on paper was that it afforded participants the opportunity to place instructions much closer to the physical pieces to be assembled than instructions viewed via computer monitor. Also, as shown in Paper II Table II, changing the communication of AR instructions from a monitor to a laptop was followed by the time taken to assemble being reduced by almost half. This may have been because participants could look at both the physical pieces and the AR information without changing the inclination of their views. Nonetheless, the medium of paper was able to communicate information to participants more quickly than computer monitor and laptop screen.

Studies 1 to 5: **Technological advances may be able to deliver production information wherever needed, but that is not the equivalent to delivering scarce manual skill knowledge wherever needed**. In particular, all participants were able to complete the assembly task successfully when following the instructions, not all of the participants were able to subsequently complete the task successfully without instructions. This happened even though participants assembled the puzzle without instructions immediately after having completed the assembly by following the instructions. This can be because the presentation of factual information is not sufficient to enable learning (Bransford et al., 1989). Hence, governments, companies, communities and individuals that are interested in the potential of AR to communicate product assembly instructions in real-time should consider the potential negative consequences that could arise if no skill learning is enabled. For example, the failure to develop and harness human expertise can lead to companies becoming uncompetitive (Davenport & Prusak, 2000).

Thus, while technological advances may be able to deliver production information wherever needed that is not the equivalent to delivering scarce manual skill knowledge wherever needed. Rather, developing manual skill knowledge involves developing adaptive expertise in discerning features that differentiate one situation from another; understanding the significance of those features; to modify or invent skills according to the requirements of that situation; and avoiding the unproductive application of previously useful prior learning in new situations. Hence, the presentation of production information wherever needed can be counterproductive if it prevents opportunities to develop the initiative needed for manual skill expertise (Schwartz et al., 2005). Accordingly, as summarized in Figure 4 below, advances in ICT, such as AR, have limited potential to enable cuts in long training durations for manual skills that are needed for anything (i.e. original one-of-a-kind goods) to be made by an increasing diversity of people.

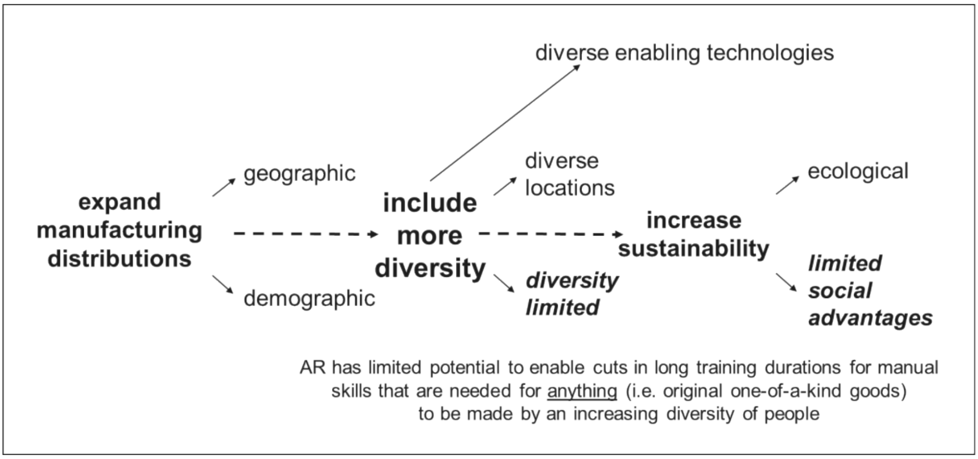


Figure 4. Long training durations for manual skills limit social sustainability

3.2 Product complexity versus sustainable distributed manufacturing (Paper III)

As explained in section 2.2., with regard to Research Question 2, *to what extent, if any, can technological advances reduce the trade-off: product complexity versus sustainable distributed manufacturing?*, technological advances need to facilitate the provision of production resources for complex products in regions that do not have necessary manufacturing infrastructures.

Research Methods

In Paper III, which is published in Technology in Society, findings are reported from a study focused on moveable factories investigating what goods should be produced by local people in regions without manufacturing skills and infrastructure?; and how can lack of manufacturing skills and infrastructure be overcome? The study focus was moveable factories because they provide a means of providing production facilities in regions that do not have industrial manufacturing infrastructures.

Moveable factories can cover rough terrain and carry their own power generation. Yet, their potential to bring about sustainable widespread modern manufacturing has gone largely unrecognized. Rather, moveable factories have been used as an occasional production solution at locations where it is not viable to establish fixed industrial manufacturing. These locations include areas in rich countries where there is need for seasonal processing of forest berries and roaming livestock, which are far from industrial infrastructure.

The study comprised literature review, semi-structured interviews, a structured questionnaire, and theory triangulation. Research participants are from regions without extensive manufacturing infrastructure: Horn of Africa and from West Africa. They are from two diaspora associations. This is because diaspora members have up-to-date knowledge of their homelands, and are often entrepreneurial with business in their homeland. Also, they seek opportunities to transfer knowledge from their diaspora country to their home land.

Semi-structured interviews were carried out separately with the chairpersons of the two diaspora associations. The semi-structured interviews led to the definition of different types of goods that the chairpersons considered could have potential for local manufacture in their home countries. The chairpersons' opinions were based on their frequent dialogues with diaspora members and with frequent contacts in their home countries, as well as their own ongoing investigations about potential business opportunities. Then, information about moveable factories was provided to diaspora association members during their separate association meetings. Next members completed a structured questionnaire. There were a total of 25 respondents: 12 from Horn of Africa and 13 from West Africa. These were diaspora associations' members who have active interest in setting up businesses in their homeland and have up-to-date knowledge of demand and supply conditions. In addition, moveable factories were analysised in terms of Resource-Based Theory, Knowledge-Based View, and Transaction Cost Economics.

Main Findings

One finding is that there are a variety of different types of moveable factories. In particular, three types of production facilities are designed and built to be operated efficiently at more than one location. Firstly, individual mobile factories that are housed within a large van or are mounted on the back of a truck in a shipping container or similar. Individual mobile factories are suitable when there is one type of production needed at a location and when production location changes daily or weekly, for example, during the processing and packaging of agricultural harvests. Secondly, sets of mobile factories that can comprise several shipping container size factory units with complementary production capabilities, such as roof truss fabrication and door set assembly. These are suitable when production location changes monthly or yearly, for example, during the construction of a group of buildings. Thus, sets of moveable factories can be deployed as flexible manufacturing systems comprising specialist manufacturing cells that enable highly efficient production of particular components.

Thirdly, modular factories that can comprise several pre-fabricated volumetric elements that are delivered by truck and are assembled to make one factory that is several times larger than a shipping container. These are suitable when production location can be fixed for up to several years and/or special internal environments are needed, for example, clean environments for production of goods containing microelectronics. Only a few types of production that need special internal environments have to be wholly within a moveable factory. Such moveable factories may need to be longer and wider than the size of a shipping container. This is because of the need to have specially covered insulated floors, walls, and roofs; as well as enough internal working space for people. By contrast, many other types of moveable factory can have work carried out around them, as well as inside them. When production is better enabled by doing so, the sides of moveable factories can open out. Then, temporary external working floors and protective roof coverings can be used to expand the work space. **Thus, there are a variety of different types of moveable factories**.

Another finding was the types of goods that participants considered could be made profitably with moveable factories. Research participants from Horn of Africa considered that the following types of goods could be made profitably with moveable factories: (1) leather goods, (2) housing blocks, bricks, lintels etc., (3) solar panels, (4) nails, bolts, brackets, handles, etc., (5) sheet roof panels, (6) fruit juice, tomato sauce, (7) water tanks and towers, (8) bread, biscuits, cakes. Research participants from West Africa considered that the following types of goods could be made profitably with moveable factories: (1) solar panels, (2) agricultural equipment such as poultry feeders, (3) food processing equipment such as maize grinders, (4) wind turbines, (5) rubbish handling equipment, (6) sanitation equipment, (7) furniture, (8) water tanks and towers. In these listings, (1) represents the goods considered to have highest potential for profitable production in moveable factories.

Differences between responses from the two respondent groups reflect different demand and supply conditions in their respective geographical regions. For example, Horn of Africa cattle herds provide a potential supply of leather for the manufacture of footwear, bags, etc. Similarly, current inefficient processing of agricultural crops was seen to offer opportunities for the mobile production of juices, sauces, bread, biscuits, etc. Also in Horn of Africa, there was considered to be unmet demand for building components needed in the local construction of houses. Many diaspora members were trying to arrange construction of houses for themselves and for others. They saw potential for the transfer of efficient western interlocking building component systems to their home countries.

By contrast, respondents from West Africa saw demand for more complex goods that could be produced in moveable factories such as poultry feeders, maize grinders, and household furniture. These goods are already available to some extent, but they were considered to be of either bad quality or high price due inefficient traditional production methods. They also emphasized the demand for equipment to handle the ever increasing amounts of packaging waste that build up on the sides of streets, and the need for more sanitation equipment. In both regions, production and installation of solar panels were seen as being an important opportunity because of erratic electricity supplies. Similarly, in both regions, water tanks and towers were seen an important opportunity due to erratic water supplies.

The participants' responses were based on consideration of demand and supply conditions. For example, there was considered to be some unmet demand for portable diesel generators due to their price being too expensive for many households. However, the respondents considered that portable diesel generators were not a good opportunity because of the difficulty of trying to produce at lower prices than mass produced Asian imports. By contrast, the sizing, framing, and installation of solar panels could be carried out more efficiently with moveable factories. Similarly, there was considered to be some unmet demand for water pumps, but the business opportunity was considered to be in the sizing, framing, and installation of water tanks and towers.

The participants were mindful of the difficulties of establishing a profitable income stream for some types of goods. For example, they were certain that individual households would pay directly for the installation of household-specific solar panels and water tanks. However, they were not certain that individual households would contribute proportionally to shared solar panels and water tanks – even though large panels and tanks could be cheaper to purchase and more efficient in operation. West African respondents saw rubbish handling as being a very urgent problem that could be addressed with equipment such as sorting bins and recycling equipment. These could be made in moveable factories. However, participants could not envisage who would pay for such goods. One participant made enquiries with the local council of his home town. He was informed that while the local council saw the build-up of rubbish as being a major problem in need of an urgent solution, they were unsure how sorting and recycling could be funded. Similarly, better sanitation was required in public spaces but they were unsure how funding could be obtained, for example, to provide and to empty watertight septic tanks. **Importantly, the goods that are needed are not as complex as goods made within the world's most advanced manufacturing infrastructures**. **Furthermore, participants did not indicate need for bespoke/ETO original products but rather MTF/MTO products are sufficient**.

A further finding is that all the goods that participants considered to have potential for profitable production can be made with moveable factories. A few mobile factories are already in use for agricultural production. A particular advantage of mobile production is that it is possible to accumulate large outputs from small contributions: in this case, local people with just one or two mango trees can carry their fruit harvest the short distance to the mobile factory as it passes by. This enables all crops to be utilized instead of only those grown on large farms. With regard to moveable bakery factory, the World Health Programme has already introduced a moveable factory to produce nutritious biscuits for Afghanistan. The moveable factory has been designed to take into account Afghanistan's intense summer heat and extreme winter cold. The moveable factory enables mixing, cutting, and packaging of biscuits containing micronutrients vital for children's growth. The factory provides work for at least twenty-five local people per working shift.

A wide range of small scale production equipment is available to support production of building components. For example, semi-automated equipment is commercially available for making components such as nails, screws, brackets, concrete blocks, metal lintels, roof trusses, corrugated sheet roofing and roof tiles. There are no fundamental barriers to combining such equipment in efficient layouts within and around sets of moveable factories. Production equipment for cutting and sewing leather into bags, sandals etc., is commercially available and can be combined in efficient layouts within moveable factories. Similarly, production equipment is commercially available for the sizing, framing, and installation of solar panels. In particular, solar panels can be built up from small solar cells and framed using basic handheld tools for cutting and drilling glass sheets and metal sections. There are no fundamental barriers to combining such equipment in efficient layouts within and around moveable factories. Also, the production equipment needed for fabrication of furniture, maize grinders, poultry feeders, septic tanks, small wind turbines, water tanks, water towers, includes conventional tools for the cutting, drilling, riveting, and fixing of sections of conventional materials such as metal and wood. For examples, water tanks can be fabricated from corrugated steel sheet. Thus, a machine for producing corrugated roof sheeting can be also used for producing sheets to be used in the fabrication of water tanks.

Mobile factories for fabrication work are already used at some remote construction site locations and at disaster locations, for example, to erect shelters as quickly as possible. The most advanced mobile factories contain digitally-driven advanced manufacturing equipment that can be used to produce complicated machine parts. Accordingly, it is also possible to produce equipment for waste handling such as compactors, as well as simpler equipment such as sorting bins. Thus, as summarized in Table 1 of Paper III on its page numbered 52, **moveable factories can be use to make MTF/MTO goods of the required complexity.** Dissertation Figure 5 below shows a comparison between a product suitable for production with moveable factories (5a) and an alternative that is too complex for production with moveable factories (5b). Figure 5a is illustrative of an Open Source Ecology kit tractor. Importantly, a kit tractor can be fabricated locally from commonly available formed materials such as standard metal box sections (Thomson and Jakubowski, 2012).

As summarized in Table 2 and Figure 1 of Paper III, another finding is that techniques used to reduce reliance on human skills in MTF and MTO factories can be applied to production in moveable factories. For example, materials conversion operations require few skills. Thus, lack of skills is not a barrier for such production. For example, a mobile fruit processing factory used in Uganda is used to more than 20 tonnes of mangoes convert per week into fruit juice. Local people bring their mangoes to the mobile factory and collect the mango juice. This enables much higher mango crop utilization and local people to increase their incomes even if they have only a small number of mango trees. The essential skill is the maintenance of the processing machinery in the mobile factory. However, this maintenance work is no more challenging than the electrical, hydraulic, and mechanical maintenance required to keep trucks driving across the rough terrain that is common in countries lacking complete road infrastructure.

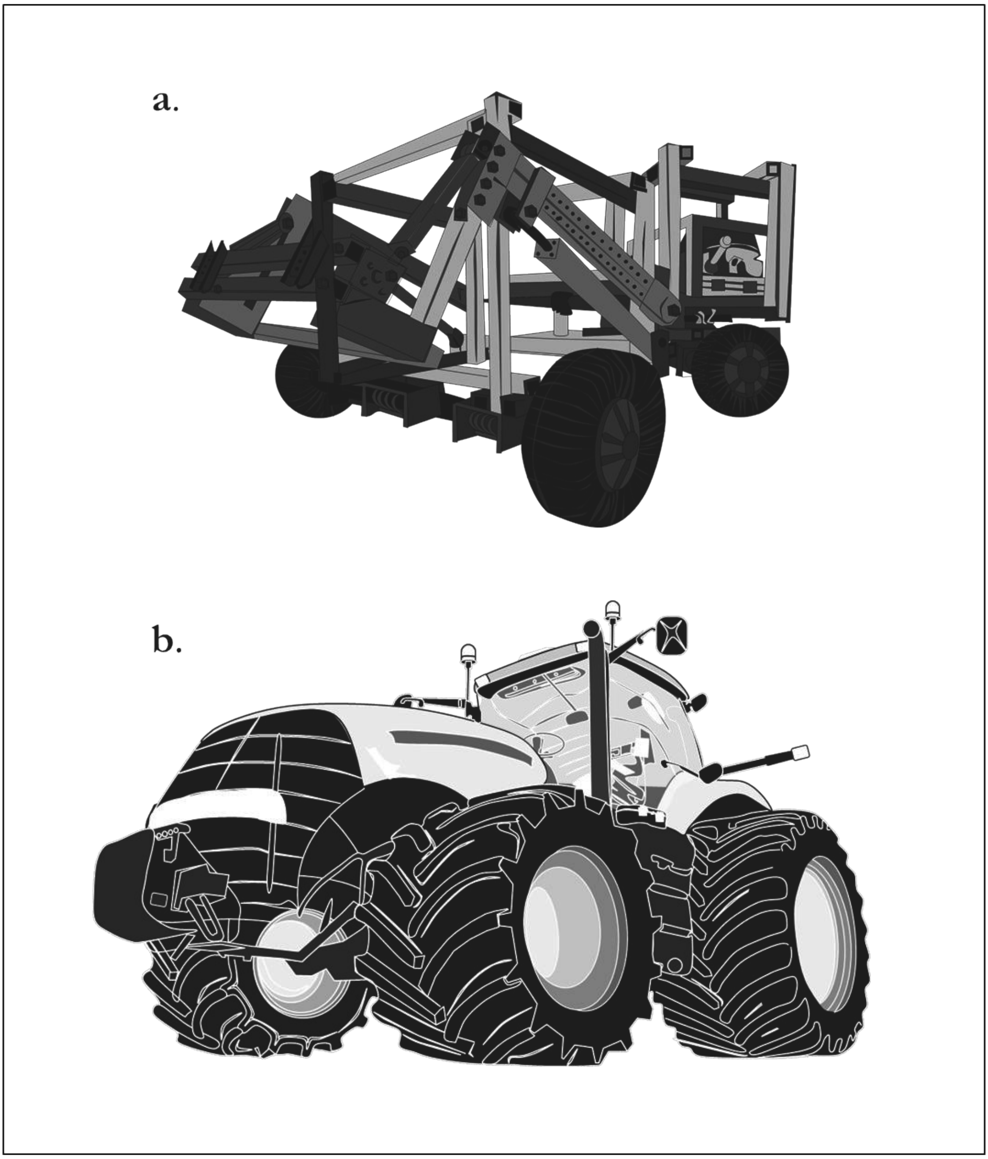


Figure 5. Low complexity product (a) compared to more complex alternative (b)

For types of production that traditionally require more skills, task analysis and job design can be applied to overcome skill shortages. Also, methods such as jigs, design for manufacture and assembly (DFMA), and visual control can be applied to reduce the reliance of successful task execution on prior skills. This is because of the replacement of task complexity with task simplicity. Task analysis etc., can be used within broader practices, such as Six Sigma, that increase process capability. In the production of physical goods, processes comprise tasks, and the production facilities, materials, methods, and people involved in carrying them out. If assessment reveals that a process is incapable, that process should be improved until reassessment indicates that it is capable.

Hitherto, consistently high productivity and quality across the world has been dependent upon global companies having fixed production facilities, such as a Toyota factory. Nonetheless, task analysis, job design, and Six Sigma are equally applicable to moveable factories. The number of tasks related to one moveable factory will certainly be less than in a large fixed factory. However, as outlined above, moveable factories can be used together as flexible manufacturing systems.

Importantly, participants did not indicate need for ETO original products but rather MTF/MTO products to which MTF/MTO techniques for reducing reliance on long training durations for human manual skills are applicable. Thus, as summarized in dissertation Figure 7, there is potential for increasing social sustainability by increasing the diversity of people involved in manufacturing.

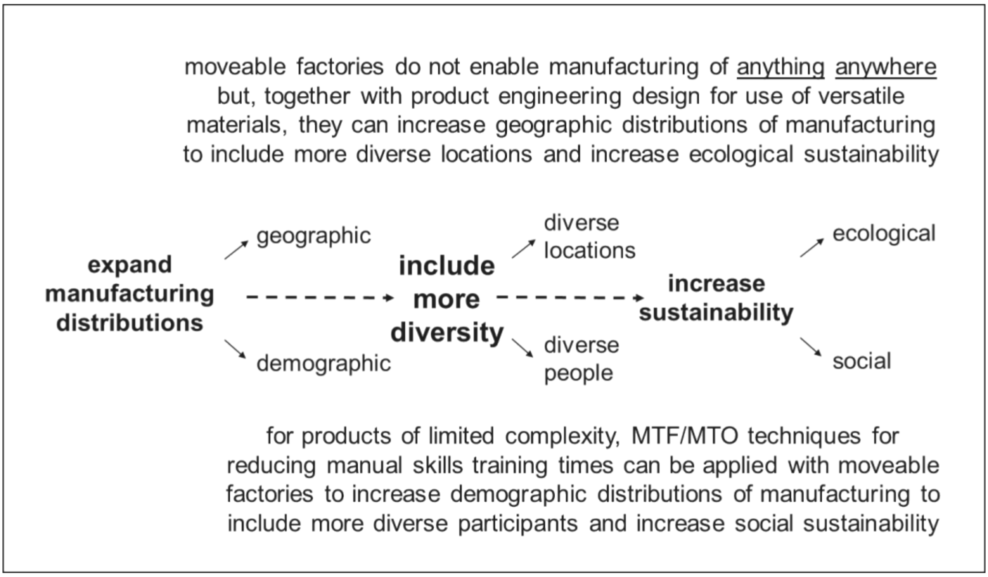
As summarized in Table 2 and Figure 1 of Paper III, a finding relating to lack of infrastructure is that the mobility of moveable factories has potential to make the supply of materials less challenging than supply of materials for fixed factories. Consider, for example, the processing and packaging of agricultural products. Within conventional industrial manufacturing, vehicles travel to the locations of farms to collect crops, livestock, etc. Then, the vehicles travel to a fixed factory location where the agricultural outputs are processed and packaged. Subsequently, more vehicles travel along more roads to wholesalers and retailers to deliver packaged goods.

By contrast, mobile factories can go where the agricultural outputs are and process them where they are. Distribution of agricultural goods processed in mobile factories can be carried out by mobile factories. Clearly, the longer the distance agricultural production is from major centres of human population, the farther the distances that have to be travelled to bring agricultural produce to consumers. However, there is far more transportation infrastructure on major routes to major centres of population than in rural areas.

Unlike the processing of agricultural outputs, the production of consumer goods and capital goods using moveable factories is more dependent upon the delivery of materials. This can be simplified by not transporting volumetric components. For example, rather than transporting a small quantity of formed plastic water tanks, enough flat metal sheets and rectangular hollow metal sections can be transported to make many water tanks and many water towers. Flat metal sheets can be formed in-situ to make corrugated metal sheets that can be used for roof coverings and for water tanks. In addition, flat metal sheets and hollow metal sections can be used to make brackets, lintels, frames and casings for vending machines, hoppers and stands for maize grinders, solar panel arrays, etc.

This example illustrates how transportation of materials to the location of moveable factories can be simplified and minimized by engineering production processes to maximise the value that is added locally by local people. Similarly, the delivery of flat timber sections can enable local production of a wide variety of value-added goods ranging from roof trusses to household furniture. Importantly, the production of capital goods and consumer goods is more likely to be carried out at one location for several months. This is different to mobile agricultural processing that can move daily. Accordingly, there is potential to hold some stocks of production materials, and so avoid total dependency on deliveries arriving at one particular time.

Thus, as summarized in **Figure 6**, **combining product engineering design for use of versatile materials with the potential for mobile factories to carry versatile materials reduces dependency on fixed manufacturing infrastructure, and has potential to increase ecological sustainability**.



moveable factories do not enable manufacturing of anything anywhere but, together with product engineering design for use of versatile materials, they can increase geographic distributions of manufacturing to include more diverse locations and increase ecological sustainability

for products of limited complexity, MTF/MTO techniques for reducing manual skills training times can be applied with moveable factories to increase demographic distributions of manufacturing to include more diverse participants and increase social sustainability

Figure 6. Increased sustainability for production of low complexity goods.

3.3 Product unsustainability versus sustainable distributed manufacturing (Papers IV and V)

As explained in section 2.3., with regard to Research Question 3, *to what extent, if any, can technological advances reduce the trade-off: product unsustainability versus sustainable distributed manufacturing?*, technological advances need to facilitate more sustainable material utilization across manufacturing distributions ranging from small-scale local distributed operations to large-scale centralized operations.

3.3.1 Potential for technological advances to facilitate sustainable materials utilization in distributed manufacturing (Paper IV)

Research Method

In Paper IV, which is published in Technological Forecasting & Social Change, findings are reported from abductive analyses concerned with advances in materials technology. Abductive analyses involve iterative cycles of reference to theories and observations to increase understanding of causation. By contrast, inductive reasoning involves moving from observation to theory; and deductive reasoning involves moving from theory to observation. Accordingly, the abductive analyses involved reference to materials science theory and observations of developments in manufacturing brought about by advances in materials technologies.

The research culminated in the formulation and testing of an analytical framework addressing fundamental factors that can indicate whether advances in materials technologies can better enable expansion of manufacturing distributions. The analytical framework facilitates comparison of established materials technologies with alternative materials technologies. Comparison is made in order to determine whether or not advances in materials technologies better meet key criteria for expanding manufacturing distributions, in particular prosumption where local people manufacture with local materials.

Main Findings

One finding is that advances in materials technologies can have advantages and disadvantages for expanding the distribution of manufacturing. Here, it is important to recognize that many advances in materials technologies that can support expansion of manufacturing distributions are not developed specifically to expand manufacturing distributions. Rather, as noted in Paper IV on page numbered 724, advances can come from industries, such as aerospace, which invest heavily in the development of materials technologies Other technologies, such as additive manufacturing, may be more associated with expanding manufacturing distributions but, nonetheless, can be advanced through investment from industries such as aerospace (Uhlmann et al., 2015). Also, it is important to recognize that advances in material technologies are relative rather than absolute. In particular, they are relative to applications of materials technologies. For example, there can be many years before an advance in composite panel technology developed for extreme aerospace applications comes to be applied to in other sectors. By which time, it may no longer by the latest advance in composite panel technology.

Irrespective of the origin of advances in materials technologies, advantages for expanding manufacturing distributions are achieved when they meet at least four key criteria. Firstly, production of original one-off goods must be possible if needed. Secondly, production needs to be local, for example, at point-of-demand. Accordingly, many production facilities need to be much smaller than the factories of traditional centralized production. This can be achieved by, for example, housing production equipment within moveable factories, which can be transported as necessary to points-of-demand. Thirdly, production needs to be safe. Hence, human exposure to dangerous temperatures and equipment is not desirable. Fourthly, production needs to be fail-safe. Thus, the amount of specialist skill knowledge involved needs to be less than that required for some traditional processes because of the need to involve ordinary people at highly distributed locations and because of the difficulty of communicating skill knowledge. Disadvantages include making person-specific, local, production more difficult. Disadvantages also include the introduction of greater production hazards and greater need for specialist knowledge. In addition, it is certainly a disadvantage if any advance in materials technology is less sustainable than existing alternatives. Hence, it is important to consider whether advances in materials technologies have some disadvantages as well as some advantages. Also, it is important to consider that there can be many challenges to overcome before potential advantages are realized (Ford & Despeisse, 2016; Oropallo & Piegl, 2016).

As summarized in Figure 2 of Paper IV on its page numbered 725, another finding is that potential from advances in materials technologies to expand manufacturing distributions can be analysed in terms of four fundamental factors: chemical compositions, internal microstructures, shaping complexities, and surface characteristics. Firstly, materials technologies often improve chemical compositions through potentially dangerous processes. For example, stainless steels get their "stainlessness" when chromium is added to molten steel in a furnace at temperatures of approximately 1300 degrees Celsius. Such processes are not well-suited to the expansion of manufacturing distributions. This is because they require very large facilities. Furthermore, as much automation as possible is needed in these facilities to achieve competitive processing times and to minimise human risks from the dangerous temperatures involved.

Secondly, materials technologies often improve internal microstructures through potentially dangerous processes. For example, rolling, forging and heat treatments of low alloy steel and aluminium alloy modify their internal microstructures so as to increase their strength, but such processes are not well-suited to the expansion of manufacturing distributions because they require very large facilities. Thirdly, the potential of materials to be shaped into alternative geometric forms depends on complex interactions between characteristics such as their strength, toughness, and resistance to fatigue. For larger components, forming moulds of several cubic meters in size may be used, together with huge hydraulic presses. Recovering the necessary investments depends upon tens of thousands of sales.

Fourthly, surface treatment processes, such as anodizing, galvanizing and painting, are often needed to give required surface properties to less expensive materials. These processes may not be well-suited to expansion of manufacturing distributions because they are potentially dangerous and can be expensive. For example, anodizing is an electrolytic passivation process used to increase the thickness of the natural oxide layer on the surface of metal parts. The process is called "anodizing" because the metal to be treated forms the anode electrode of an electrical circuit. Galvanizing refers to coating the steel parts with zinc, usually in a bath that contains molten zinc metal.

Thus, established processes for production of versatile components, which as explained in section 3.2. are needed to support wider spread production, do not meet all criteria for expanding manufacturing distributions. For example, they are not easily adapted to housing within moveable factories. Moreover, they can involve human exposure to dangerous temperatures and equipment. Hence, **advances in materials technologies are needed in order to expand the manufacturing distribution of versatile components, such as metal box sections, which can support wider spread production**. This can be considered to be an unusual direction for advances in materials technologies, because it is a direction that is not focused upon developing new materials for new types of components. Rather, it is focused on enabling the processing of established materials into established components, such as metal box sections, to be carried out safely and reliably at more locations by more people. Thus, it is concerned with the adaptation of established processes for converting established materials into established components.

As summarized in Figure 3 of Paper IV on its page numbered 728, another finding is that advances in materials technologies that enable expanded distribution of small products manufacturing may be no more sustainable than previous manufacturing. For example, the properties of materials used in MTO watch casing have done little to hinder the introduction of original watch casings made by 3D printing. Here, 3D printing has the advantages of eliminating the need for product-specific molds and the alternative of skills needed for metal turning on a lathe. Moreover, 3D printing can produce very complicated geometric forms as one single piece. By contrast, two or more components may have to be made separately, and then joined together, when molds or lathes are used.

However, with regard to chemical composition, the metal alloys used in 3D printing are similar to the metal alloys traditionally used for watch casings. Accordingly, large-scale alloying processes are required to produce the metals used in 3D printing. Thus, there are neither upstream advantages nor disadvantages. With regard to internal microstructures, rolling and forging are not required for the metal alloys used in 3D printing. However, they do have to be atomized to produce the necessary metal alloy 3D printing powders. Hence, upstream advantages are cancelled out by upstream disadvantages. With regard to shaping complexities, 3D printing offers more geometric freedom than traditional production processes, and makes the manufacture of unique geometries less complicated. Accordingly, 3D printing offers a clear advantage. With regard to surface characteristics, 3D printing components produced with metal alloys may require some grinding and polishing, depending on the finest of metal powders used. So, 3D printing does not offer a notable advantage. Thus, **advances in materials technologies that enable expanded distribution of small products manufacturing may be no more ecologically sustainable than previous manufacturing**.

As summarized in Figure 4 of Paper IV on its page numbered 730, another finding is that advances in materials technologies that enable expanded distribution of large products manufacturing may be no more sustainable than previous manufacturing. For example, DIY manufacturing of vehicle bodies involves use of composites, rather than metal, for body panels. By use of composite body panels, rather than metal body panels the company avoids major overhead costs from large moulds and presses. Compared to metals technologies relevant to car body panels, there is much more innovation in composite technologies. With regard to chemical composition, metals are not needed in composite panels. Accordingly, large-scale metal alloying processes are not required.

On the other hand, the processes needed to produce fiberglass, resins and plastics also require large-scale capital investments in processing equipment. Moreover, a greater diversity of processes is required to produce the greater diversity of material involved. Hence, the upstream advantages are cancelled out by upstream disadvantages. With regard to internal microstructures, rolling, forging and heat treating are not required for composite panels. However, achieving the correct internal microstructures can be more challenging for composite panels than for sheet metal. This is because composites comprise several materials rather than just one. Moreover, the different materials have different properties. Conventional thermoplastic polymers, for example, can become brittle in cold weather or can become soft and warp in hot weather.

Accordingly, different thermoplastic polymers are developed with modified properties to suit the performance requirements of different products. Heavy-duty composites, for example, can use thermosetting polymers that are less vulnerable to heat, and have better mechanical properties. However, they are more difficult to mould into a large shape that is complicated in three-dimensions. Thus, as summarized in **Figure 7** below, sustainability benefits are questionable as there are advantages and disadvantages. With regard to shaping complexities advantages, composite panels offer equal geometric freedom to traditional production processes, but without the need for such heavy industrial equipment. With regard to surface characteristics, composite panels offer the important advantages of eliminating the need for galvanizing and painting. This is because weather protection and colour can be manufactured into composite panels through the combination of appropriate plastics. There is, however, potential for increased risk of ultraviolet radiation (UV) damage, which could shorten vehicle life-span and lead to increased vehicle production. Hence, **advances in materials technologies that enable expanded distribution of large products manufacturing may be no more ecologically sustainable than previous manufacturing**.

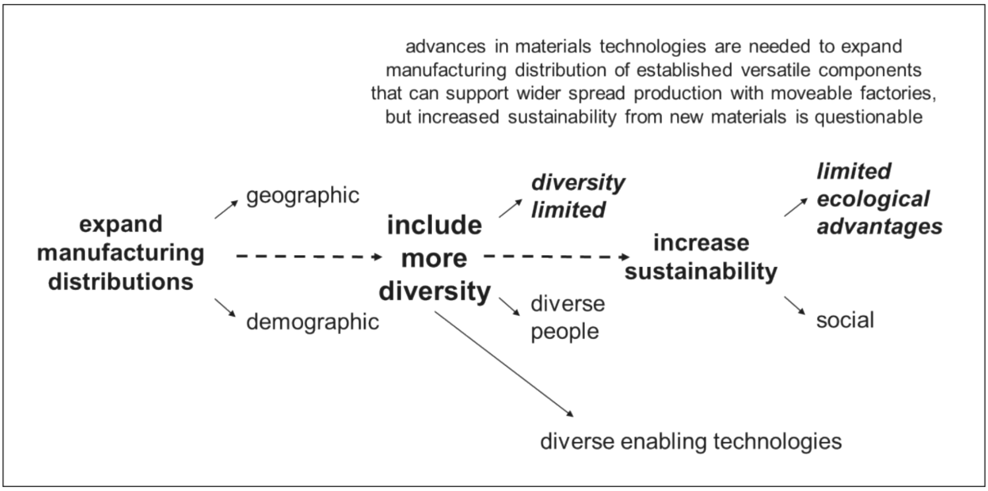


Figure 7. Advances in materials technologies needed

3.3.2 Potential for technological advances to facilitate sustainability across many manufacturing distributions (Paper V)

Research Method

In Paper V, which is published in the Journal of Cleaner Production, findings are reported from case study including literature review and field study. Literature review was extended from scientific papers and monographs to include online reports etc. The inclusion of this grey literature enables multi-vocal literature reviews, which are necessary when information relevant to a topic is disseminated via diverse media channels. Field study involved gathering of information by face-to-face, telephone and email. The research concluded in the formulation of a taxonomy of manufacturing distributions and their comparative relations to categories of sustainability.

Main Findings

As summarized in Figure 1 of Paper V on its page numbered 1824, one finding is that there are already many distributions of manufacturing. In particular, distributed manufacturing can be categorized as DIY, artisanal, industrial and centralized. DIY manufacturing encompasses the three waves: subsistence (*1st wave*) industrial (*2nd wave*) and post-industrial (*3rd wave*). Artisanal manufacturing encompasses craft-based manufacturing of specialty cheeses, wines, etc., at farms (*rural*), manufacturing at retail outlets such as patisseries, tailors, etc. (*urban*), and manufacturing of easily posted goods by Web-based businesses (*Web*). Industrial distributed manufacturing encompasses manufacturing of components (*parts*); semi knocked-down kits and complete knocked-down kits (*S/CKD*); and complete goods (*products*). Centralized manufacturing includes large scale conversion processes for materials (*large process*), assembly of physically massive complete goods (*large assembly*), clusters of interconnected organizations (*geo cluster*). Thus, **there are already many types of manufacturing distributions**.

As summarized in Figure 1 and Table 2 of Paper V, another finding is that some existing distribution of manufacturing have sustainability advantages. For example, car production in Turkey. In 2017, automotive manufacturing is concentrated in the Marmara *geo cluster*. However, the Turkish government seeks to increase manufacturing in the southeastern part of the country by establishing there a new geographical cluster for production. Companies that move their production plants to these regions will be exempt from corporate tax. While this may greatly increase social sustainability in the southeastern Turkey, increases in ecological sustainability are less certain. For example, when new cars are needed in south-eastern Turkey they are driven some 1200 kilometers by car-carrying truck from Marmara at a 2016 price of about 250 US dollars (USD) per car. This is because car manufacturing in Turkey is centralized in an existing *geo cluster* in Marmara.

Hitherto, there has not been car production in the southeastern region due to lack of local demand and the relatively small additional price for vehicle delivery of about 250 USD. From an ecological perspective, the impact of transporting 12 cars across some 1200 kilometers on a car-carrying truck is small compared to the total ecological impact of producing 12 cars. Furthermore, if there is increased car demand in the southeastern region, extending existing factories in the Marmara region could have relatively low ecological impact. This is because necessary roads and other infrastructure have already been constructed in Marmara. Whereas, completely new factories and infrastructure would have to be constructed in the southeastern region.

A wide range of factories, including raw materials processing, could be constructed in the southeastern region. However, subsequent economic and ecological costs of transporting raw materials from the ports of Marmara region to the southeast region would be high. Hence, there is little, if any, justification for constructing material processing plants in the southeastern region. An alternative would be to construct one large assembly plant in the southeastern region, and transport parts manufactured in Marmara to the southeastern region. The break-even for such an investment would depend upon a huge increase in demand in the southeastern region. This is because thousands of cars per week need to be produced in large-assembly plants.

Thus, existing distribution of manufacturing have comparative advantages for ecological and social sustainability. Hence, expansion of manufacturing distributions should be selective, and not based on hype that reduces complex reality of production location optimization to overly simplistic assertions such as reducing the number of big factories and increasing the number of small factories will improve the sustainability of production.

As summarized in Figure 1 and Table 2 of Paper V, another finding is that some alternative distributions of manufacturing have some sustainability disadvantages. For example, an alternative would be to construct "mini-factories" for car production across the southeastern region. This, however, could have higher ecological impact than constructing one large assembly plant. For example, new ground would have to be dug up in more new places. All of this would come at construction costs, which could not equal the economies of scale associated with constructing one large factory at one location. If the assembly mini-factories were operated with a high level of automation, any sustainability advantages compared to transporting new cars 1200 kilometers from Marmara are unclear. This is because few local manufacturing jobs would be created and the ecological impacts arising from manufacturing and operating automation equipment could be high.

If human workers assembled semi or complete knock-down kits there would at least be the advantage of creating local employment. On the other hand, there would be additional ecological impacts of packaging and protecting the kits as they are transported from the Marmara region. If the manufacturing of parts were carried out in the southeast region, there would be the environmental and financial costs of transporting processed materials such as steel bars and sheets from Marmara. However, this would create more local employment and boost social sustainability.

Other distributions of manufacturing for automotive production in the southeastern region of Turkey also have few, if any, sustainability advantages compared to transporting cars from Marmara. 1st wave DIY and artisanal production are not relevant. This is because they are not economically viable due to technical constraints and inordinate amount of time required to make cars by hand. 2nd wave DIY is relevant as consumer car kits are a well-established niche in DIY. However, the ecological impact of transporting a consumer car kit from the ports of Marmara can be at least equal to transporting a completed car. This is because the transportation of complete cars is a refined system based on delivery optimization using car-carrying trucks that can move 12 vehicles together. By contrast, transporting consumer car kits involves individual handling and transportation.

Third wave DIY is relevant as local options for vehicle production, such as those introduced by LocalMotors.com, are already becoming established in 2017. Those which offer the best improvements for production sustainability are those that involve least transportation of materials, parts, and kits from Marmara region, while entailing the most human employment. Such opportunities arise from production based on 3rd wave DIY open source vehicle designs, which have been developed to make maximum use of standard multi-purpose components. An important feature of 3rd wave DIY vehicle production is that it is not based on the notion of having to construct fixed factories. Rather, vehicle production can be moved from location to location as needed to meet individual demand as it arises. However, this is no more a perfect solution than any other distribution of manufacturing. Rather, it also brings disadvantages such as limited potential to achieve economies of scale equal to those that can be achieved in a fixed geographical cluster.

Thus, as summarized in dissertation Figure 8, **expanding the distribution of manufacturing does not necessarily increase the ecological and social sustainability of manufacturing. Rather, in some situations, centralized manufacturing that optimizes materials utilization can have higher potential for ecological sustainable production than other distributions of manufacturing**.

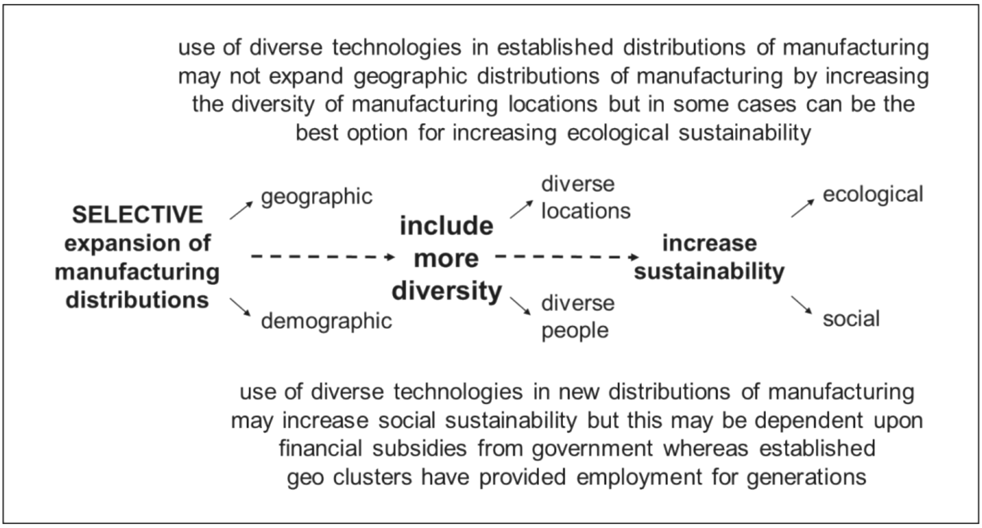


Figure 8. Expansion of manufacturing distributions is not always best option.

4 DISCUSSION

In this section, discussion is provided of contributions to addressing the research questions and to testing the hypothesis. In addition, theoretical and practical implications are described. Also, the limitations and generalizability of the research is discussed.

4.1 Research questions and research findings

In this sub-section, contributions to addressing the research questions are discussed.

4.1.1 Research Question 1 (Papers I and II)
Product originality versus sustainable distributed manufacturing

As explained in section 2.1., with regard to Research Question 1, to what extent, if any, can technological advances reduce the trade-off: product originality versus sustainable distributed manufacturing?, technological advances need to facilitate wherever required, without compromising potential for product originality: reduction of wasteful production iterations and the provision of scarce manual skill knowledge.

Findings reported in Paper I indicate that technological advances have limited potential to reduce wasteful production iterations of work and rework without compromising product originality. In particular, the convergence of virtual-social-physical technologies (VSP), which it has been claimed to contribute to people being able to make anything has little potential to bring about major reductions in overall times and costs that could increase demand and enable expansion of large-scale ETO manufacturing. Rather, the greatest potential for VSP is in DIY manufacturing of small bespoke goods by individuals and communities who do not have the risks facing established bespoke manufacturers such as brand dilution.

Findings reported in Paper II indicate that the design of information and its communication are at least as important as advances in information and communication technologies (ICT) such as Augmented Reality (AR). For example, finding reported in Paper I indicate that the communication of information on pieces of paper can be more successful than the communication of information by AR. Moreover, findings reported in Paper I provide further support for previous research in other fields that presenting production information is not sufficient for the development of skills, and can even be counterproductive (Schwartz et al., 2005). Advances in ICT have been applied to develop platforms for skills training. However, these have been developed for MTF and MTO work (Webel et al, 2013): rather than bespoke/ETO work where product originality brings greater production unpredictability. Meanwhile, skill shortages persist (Bryson et al., 2018).

Thus, as summarized in dissertation **Figure 9** below, **the extent to which technological advances reduce the trade-off between the originality of large products and sustainable distributed manufacturing continues to be limited by factors, which as explained in subsection 2.1, have limited besoke/ETO production in the past**. In particular, lack of product standardization limits production standardization that facilitates reduction of reliance on wasteful production iterations and scarce human manual skills.

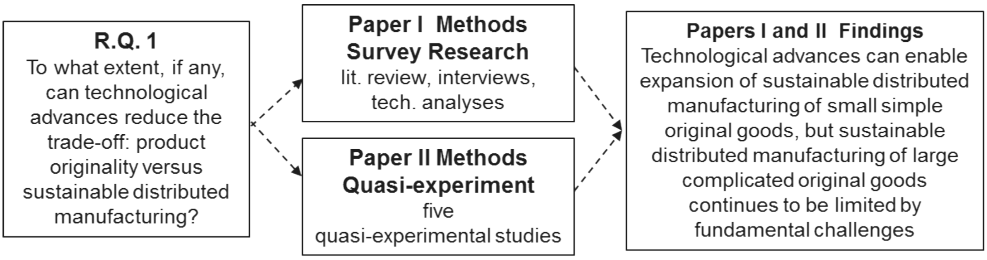


Figure 9. Research Question 1, Methods, and Findings

4.1.2 Research Question 2 (Paper III)
Product complexity versus sustainable distributed manufacturing

As explained in section 2.2., with regard to Research Question 2, *to what extent, if any, can technological advances reduce the trade-off: product complexity versus sustainable distributed manufacturing?*, technological advances need to facilitate the provision of production resources for complex products in regions that do not have complex manufacturing infrastructures.

Findings reported in Paper III indicate that there are different types of moveable factories that can be used to make goods that are sufficiently complex to meet demand for many products in regions without advanced manufacturing infrastructure. However, these goods are basic capital goods such as water tanks and simple consumer goods such as household furniture: rather than very complex goods. Moreover, findings indicate demand for MTF/MTO goods rather than bespoke/ETO original products. Thus, techniques used for reducing reliance on human manual skills and reducing training durations for manual skills, such as task analysis, DFMA, job design are applicable for MTF/MTO production with moveable factories.

Furthermore, findings indicate that engineering products for production with versatile materials such as galvanized metal sheets and box sections can reduce dependency on fixed manufacturing infrastructure. Overall, findings indicate that technological advances in moveable factories, when supported by relevant product and production engineering practices, can expand the distribution of manufacturing that has some advantages for ecological and social sustainability. Findings indicate that rather than technological advances enabling anything to be made anywhere, technological advances in moveable factories better enable some basic MTF/MTO capital and basic MTF/MTO consumer goods to be made away from advanced manufacturing infrastructures.

Thus, as summarized in dissertation Figure 10 below, findings indicate the trade-off between the most complex products and sustainable distributed manufacturing continues to be limited by the same fundamental factors, which as explained in subsection 2.2, have limited manufacturing locations for complex products in the past.

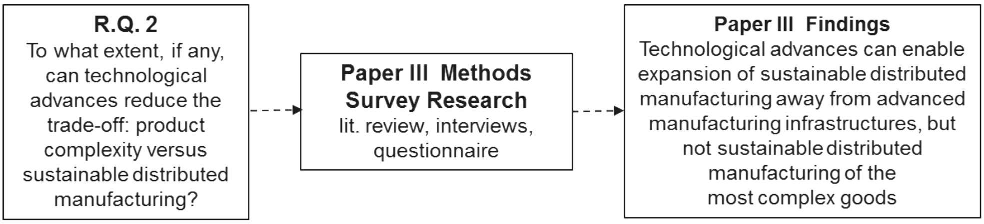


Figure 10. Research Question 2, Methods, and Findings

4.1.3 Research Question 3 (Papers VI and V)
Product unsustainability versus sustainable distributed manufacturing

As explained in section 2.3., with regard to Research Question 3, *to what extent, if any, can technological advances reduce the trade-off: product unsustainability versus sustainable distributed manufacturing?*, technological advances need to facilitate more sustainable material utilization across manufacturing distributions ranging from small-scale local distributed operations to large-scale centralized operations.

As summarized in Figure 11, findings reported in Paper IV indicate that advances in materials technologies are needed in order to expand distribution of manufacturing of versatile components such as standard metal box sections, which otherwise continue to involve hazardous industrial processes. However, findings indicate that advances in materials technologies can have some disadvantages as well as some advantages for expanding sustainable distributed manufacturing. For example, advances in materials technologies that enable expanded distribution of large products manufacturing may be no more sustainable than previous manufacturing. Accordingly, advances in materials technologies should be applied selectively.

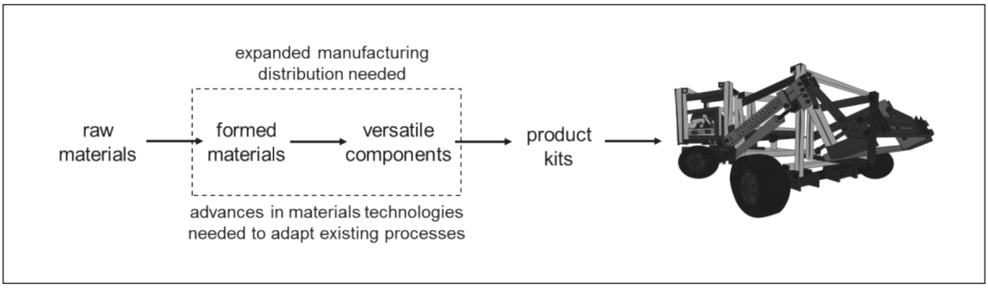


Figure 11. Need to expand distribution of manufacturing of versatile components

Findings reported in Paper V indicate that there are already many distributions of manufacturing. Moreover, expanding the distribution of manufacturing does not necessarily increase the sustainability of manufacturing. Rather, in some situations, centralized manufacturing, for example in *geo clusters*, can have higher potential for sustainable production than other distributions of manufacturing. Thus, rather than technological advances enabling sustainable manufacturing of anything anywhere, often technological advances can be best deployed in improving the sustainability of manufacturing where it is already established.

Hence, as summarized in dissertation **Figure 12**, **the extent to which technological advances reduce the trade-off between product unsustainability and sustainable distributed manufacturing depends upon them being applied selectively to improve old manufacturing processes and distributions, alongside enabling new processes and distributions.** For example, improvements are needed to the processing of materials into versatile components, such as standard metal box sections, alongside reductions to the size and weight of production equipment that facilitate moveable factories.

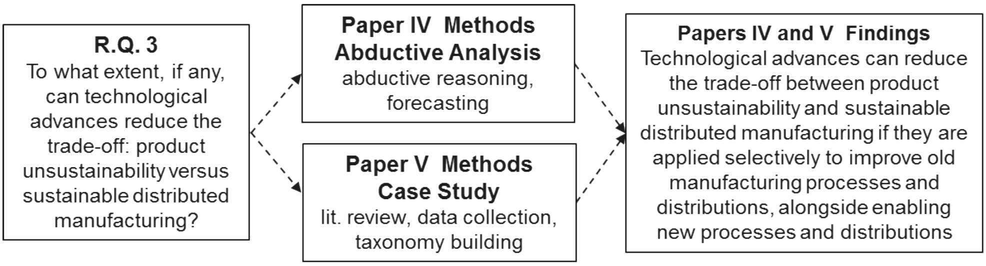
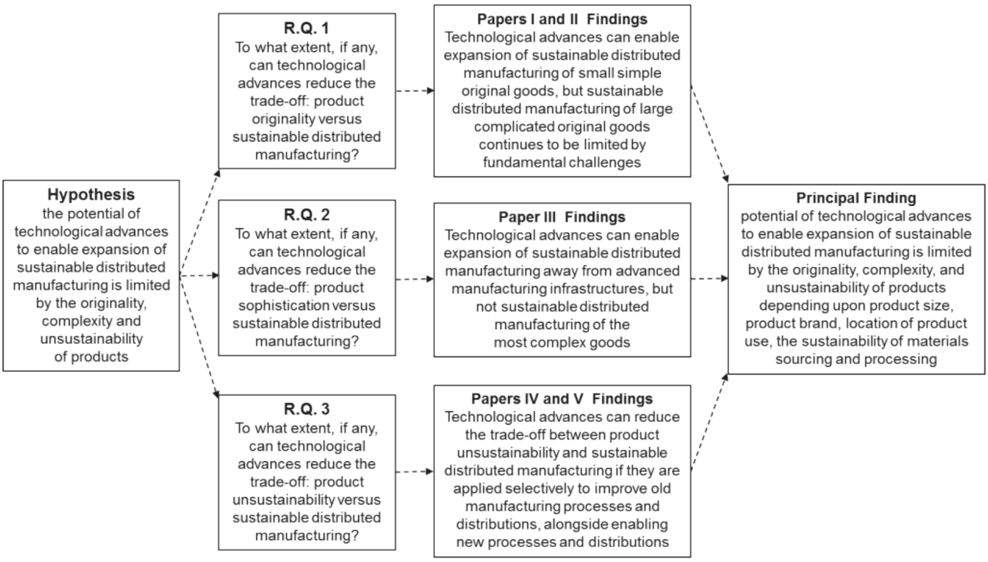


Figure 12. Research Question 3, Methods, and Findings

4.2 Research hypothesis and principal finding

Findings reported in Papers I and Paper II indicate that technological advances enable expansion of sustainable distributed manufacturing of original products, if the products are small simple unbranded products rather than small branded products or large complicated products. Findings reported in Paper III indicate that technological advances enable sustainable distributed manufacturing of products that are more complex than could otherwise be made far from advanced manufacturing infrastructures, but which nonetheless are not the most complex of products. Findings reported in Papers IV and V indicate that technological advances enable more sustainable distributed production of products with unsustainable features, if technological advances are applied to some existing manufacturing processes and distributions, as well as to enable new manufacturing processes and distributions. Thus, as summarized in dissertation **Figure 13** below, findings indicate that the scope of the hypothesis:

the potential of technological advances to enable expansion of sustainable distributed manufacturing is limited by the originality, complexity, and unsustainability of products is not universal. Rather, the branding and size of products mediates the limitations brought by product originality. For example, a small original decorative object can be 3D printed on a home-made open source 3D printer by somebody who does not have traditional manual production skills, but an original cruiseliner needs to be built by people who do have traditional manual production skills. Also, the location of product use mediates the limitations brought by complexity. For example, a solar array made with a moveable factory is a more complex product than could otherwise by made in a fragile region far from manufacturing infrastructure. Furthermore, technological advances to improve the sustainability of raw materials processing can be enforced more rigorously at different sources: for example, monitoring and enforcement are more easily focused on large-scale centralized production plants than at highly distributed artisanal operations.



Hypothesis
the potential of technological advances to enable expansion of sustainable distributed manufacturing is limited by the originality, complexity and unsustainability of products

R.Q. 1
To what extent, if any, can technological advances reduce the trade-off: product originality versus sustainable distributed manufacturing?

R.Q. 2
To what extent, if any, can technological advances reduce the trade-off: product sophistication versus sustainable distributed manufacturing?

R.Q. 3
To what extent, if any, can technological advances reduce the trade-off: product unsustainability versus sustainable distributed manufacturing?

Papers I and II Findings
Technological advances can enable expansion of sustainable distributed manufacturing of small simple original goods, but sustainable distributed manufacturing of large complicated original goods continues to be limited by fundamental challenges

Paper III Findings
Technological advances can enable expansion of sustainable distributed manufacturing away from advanced manufacturing infrastructures, but not sustainable distributed manufacturing of the most complex goods

Papers IV and V Findings
Technological advances can reduce the trade-off between product unsustainability and sustainable distributed manufacturing if they are applied selectively to improve old manufacturing processes and distributions, alongside enabling new processes and distributions

Principal Finding
potential of technological advances to enable expansion of sustainable distributed manufacturing is limited by the originality, complexity, and unsustainability of products depending upon product size, product brand, location of product use, the sustainability of materials sourcing and processing

Figure 13. Research Hypothesis and Principal Finding

As shown in Figure 13, the principal finding can be stated as follows:

the potential of technological advances to enable expansion of sustainable distributed manufacturing is limited by the originality, complexity and unsustainability of products depending upon product brand, product size, location of product use, the sustainability of materials sourcing and processing.

4.3 Limitations and generalizability

Overall, the five papers upon which this dissertation is based have provided improvements to previous explanations about potential for expanding sustainable distributed manufacturing. Nonetheless, the research summarized in this dissertation is limited by having involved only five studies, and each of those having limited scope. For example, the survey research reported in Paper I involved only ten experts alongside literature review. Also, the quasi-experiments reported in Paper II involved only 92 participants. Furthermore, the analytical cases in reported in Paper VI involved only two main examples. However, survey research reported in Paper I, the quasi-experiments reported in Paper II, and abductive analysis reported in Paper IV addressed underlying issues that are not limited to the specific examples. For example, the analysis criteria introduced in paper IV are generalizable irrespective of sector. In particular, chemical composition, internal microstructures, shaping complexities, and surface characteristics are relevant to all materials that could be used in manufacturing.

The research also has geographical limitations. For example, the study reported in Paper III had respondents from only one country in West Africa and from one country in the Horn of Africa. However, with regard to generalizability of the findings, it can be seen that differences per capita GDP are reflected in the types of goods seen as having potential for profitable production. In particular, the per capita GDP of West African respondents' homeland is four times higher than that of Horn of Africa respondents'. Accordingly, construction goods were seen as opportunities by Horn of Africa respondents from low population density low GDP regions in need of less rudimentary housing. By contrast, challenges of waste handling and public sanitation were seen as important to West African respondents. This is because their home towns were suffering from increasing build-up of waste from food packaging, consumer goods packaging, etc., as their population density and GDP increased. Similarly, the case study in Paper V was focused on only one country, Turkey. All of the 12 kinds of manufacturing distributions of the taxonomy were found to be present in Turkey, whereas some of them may not be present in other countries. Nonetheless, the taxonomy of manufacturing distributions can be applied to any country.

The generalizability of the findings could be limited by the passage of time. Thus, far however, issues identified in the five papers continue to be relevant to the expansion of sustainable distributed manufacturing. For example, virtual-social-physical convergence (VSP) has not ended reliance in bespoke/ETO production on iterations of work/rework with traditional subtractive processes that involve material wastage and production inefficiencies (Paper I). Rather, bespoke/ETO companies still try to move towards MTO, which reduces their reliance on traditional wasteful iterations as they transform each individual customer's idea into a completed product (Christensen & Brunoe, 2018). For example, with regard to Paper II, the application of AR in the practice of manual skills training for manufacturing work continues to be limited (Masood & Egger, 2019). Meanwhile, research by others continues to overlook the potential to improve established alternatives, such as paper-based instruction, which can be more robust alternatives in regions without manufacturing infrastructure, reliable Internet coverage etc. (Gavish et al., 2015). With regard to Papers III and IV, the potential of moveable factories to expand sustainable manufacturing distributions has become more widely recognized (Paper III), including the potential for advances in materials technologies to enable materials processing with moveable factories (Paper IV) (Kate et al., 2017). Also, as reported in Paper V, a forecast by the author that was published in 2014 about limited potential for innovative DIY manufacturing without subsidy has been supported by subsequent contraction of related DIY manufacturing enterprises (Malone, 2017).

More broadly, product originality and product complexity continue to exert an important influence over manufacturing distributions. For example, reshoring of some previously off-shored manufacturing back to the home countries of global manufacturing companies can be economically viable when robots become cheaper and more efficient. Also, the inclusion of robots in moveable factories could become economically viable for production away from manufacturing infrastructures. However, the more original and complex products are, the more difficult it is to automate production fully even with artificial intelligence. With regard to product originality, this is because artificial neural networks and reinforcement learning have limitations in dealing with change. In particular, their performance can rely on the number of cases available as training data and to direct automatic labelling. This reliance can be problematic when there is low repetition of cases or when each case is somewhat original. Although it may be possible in the future for virtual simulation methods to generate new labelled data samples from a few real data samples, such solutions require capital investment and computational expertise that are beyond the scope of small bespoke/ETO companies. Also, bespoke/ETO production can be considered to be sparse reward environments for reinforcement learning when exactly what has to be learnt keeps changing as new bespoke/ETO customers have new individual requirements. Inverse reinforcement learning that extracts a reward function from observed behaviour is also of limited usefulness when behaviour needs to change frequently as new bespoke/ETO customers come and go (Kiumarsi et al., 2018).

4.4 Contributions to science

Findings reported in this disseration, and the five papers upon which it is based, have a common theoretical implication. That is, different manufacturing distributions are affected by three common underlying fundamental trade-offs. By contrast, literature by others has focused on industrial manufacturing or DIY manufacturing, while much less consideration was given to artisanal production. The research culminates in a taxonomy of manufacuring distributions and their comparative relations to sustainability. This provides specificity in definition of manufacturing distributions that is needed to analyse different options for improving production sustainability. The taxonomy of manufacturing distributions encompasses three kinds within each of four types of manufacturing distributions: DIY, artisanal, industrial, and centralized manufacturing, which are related to categories of sustainability. Notably, the research found no compelling evidence that any one distribution of manufacturing will inevitably increase the sustainability of production: especially in the long-term. Rather, production sustainability is affected by many inter-related factors.

The inclusiveness of the research provides examples illustrating, as summarized in Figure 14 below, that the constraining influence of the three trade-offs can be (a) latent or (b) manifest depending upon contextual factors, which include brand issues as well as production issues. For example, fabrication of essential capital goods can be achieved through simple standardized goods comprising common versatile components (Figure 14a). By contrast, bespoke/ETO production of luxury goods can involve making complex original one-of-a-kind goods comprising rare materials transported from far distant locations (Figure 14b). The dissertation makes explicit the constraining influences of the three fundamental trade-offs, and how manufacturing distributions can be away from or close to their constraining influence. This can enable fundamental trade-offs, and potential to manage their constraining influence, to be recognized from the outset in debate amongst governments, companies, communities and/or individuals about expanding sustainable manufacturing distributions. This has relevance to theory concerned with enabling shared understanding across communities of practice (Star, 1989; Wenger, 1998).

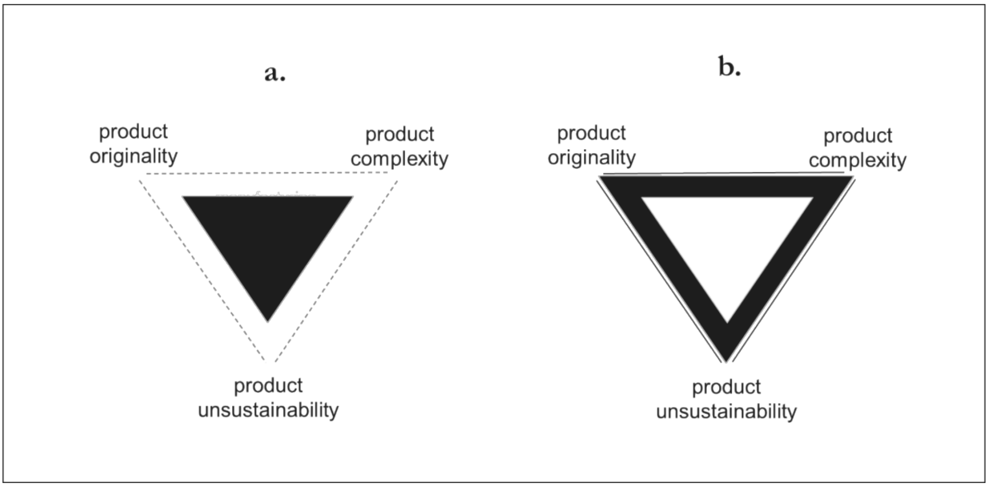


Figure 14. Latent constraints away from trade-offs (a)
and manifest constraints close to trade-offs (b)

Furthermore, the connecting of hitherto separately considered manufacturing distributions reveals the broad applicability of extant engineering design theory (Eastman, 2012; Stjepandić et al., 2015). For example, process capability and statistical process control are as important for production in a moveable factory as in a large process plant. Moreover, the research draws attention to the need for concurrent engineering of products, manufacturing processes and manufacturing distributions. In particular, products need to be designed for the appropriate sustainable manufacturing distribution. These can be very different. For example, a more sustainable manufacturing distribution in a developed country that has extensive industrial infrastructure may be a distribution that improves the sustainability of "first mile" and "last mile" logistics. This can be done by concurrent engineering to faciliate deployment of moveable factories that improve "first mile" logistics by materials processing and packaging at source of supply; and improve "last mile" logistics by efficient manufacturing at point-of-demand. By contrast, establishing a sustainable manufacturing distribution in a fragile nation with no industrial infrastructure can depend upon products being designed for limited originality, minimum complexity and maximum use of common versatile components. This being necessary in order to facilitate the scaling up of local production by local people who lack experience in production work. Thus, established concurrent engineering methodologies are as relevant to new manufacturing distributions as they are to established manufacturing distributions. For example, Design for Assembly is as relevant to engineering design of a tractor kit (Figure 5a) to be assembled with moveable factories as to engineering design of a conventional tractor (Figure 5b) to be assembled in a conventional factory.

In addition, the dissertation brings together research encompassing a wide range of digital and physical technologies. The research reveals that adaptations of established technologies can facilitate sustainable distributed manufacturing away from the constraining influence of the three trade-offs (Figure 14a). For example, fabrication of essential capital goods, such as tractors (Figure 5), needs to be scaled up in many parts of the world, and this can be achieved through flat-packed kits and moveable factories (Figure 5a), i.e. technology adaptations. Thus, scaleable technologies for leapfrogging over the need for conventional industrial infrastructure (Fong, 2009) do not always have to be the latest cutting-edge technologies. Hence, the research is relevant to debate concerned with appropriate technology. In particular, technology that is socially and environmentally approprate for sustainable development (Evans, 2019).

4.5 Contributions to practice

Findings reported in the five papers have practical implications for all interested in expanding sustainable distributed manufacturing. For individuals and communities interested in expanding the distribution of DIY manufacturing, findings in Paper I are positive as they indicate where technological advances have most potential. By contrast, findings in Paper I are far less encouraging for established manufacturers as they indicate that technological advances could dilute current brands in bespoke production and are of limited usefulness for ETO production of large products.

Findings reported in Paper II reveal some limitations in advances in information and communication technologies such as AR. In particular, instructions viewed on pieces of paper and laptops may be more useful than the same instructions viewed through more sophisticated ICT. Also, findings in Paper II draw attention to the limitations for real-time communication of production information to contribute to the development of manual skills.

Findings reported in Paper III show that moveable factories can be used to produce much needed goods far from manufacturing infrastructures: provided there is careful application of established production engineering techniques in product development. In particular, product engineering design for use of versatile standard components is important alongside application of task analysis, job design, etc.

Findings in Paper IV draw attention to advances in materials technologies being needed to expand distribution of manufacturing of versatile components such as standard metal box sections, which otherwise continue to involve hazardous industrial processes. However, findings indicate that advances in materials technologies can have some disadvantages as well as some advantages for expanding sustainable distributed manufacturing. Hence, careful analyses of materials and processes are needed in order to determine the potential of technological advances expand sustainable distributed manufacturing. In Paper IV, an analytical framework is provided to facilitate such analyses.

Findings in Paper V indicate that expanding the distribution of manufacturing does not necessarily increase the sustainability of manufacturing. Rather, in some situations, centralized manufacturing in *geo clusters* can have higher potential for sustainable production than other distributions of manufacturing. Thus, rather than technological advances enabling sustainable manufacturing of anything anywhere, technological advances can often be best deployed to improve sustainability at existing manufacturing locations.

The research has led to the author being invited to the steering committee of India's Inclusive Manufacturing Forum, and cooperating with the Finnish Foreign Ministry's Finnpartnership programme for developing countries. This suggests that practical implications may be most for countries experiencing premature deindustrialization. However, there are related practical implications for countries with expertise in the development of sophisticated manufacturing technologies. For example, as summarized in dissertation Figure 11, such expertise is needed to adapt some established material conversion and component manufacturing processes for operation in moveable factories. Thus, there can be mutual prosperity growth between countries. Some countries can supply a key enabling technology. Other countries can apply the technology to enable expansion of sustainable manufacturing distributions by local people using local materials.

5 CONCLUSIONS

5.1 Contributions

The background of the research reported in this dissertation is interest among governments, companies, communities, and individuals in sustainable distributed manufacturing. Technological advances have potential to expand the distribution of manufacturing, which can introduce opportunities for improved ecological and social sustainability. However, many claims for enabling technologies and distributed manufacturing have characteristics of vague hype. Consider, for example, the title of an article in the scientific journal Nature: Make anything, anywhere (Mandavilli, 2006). Yet, those countries that dominated global manufacturing 10 years ago continue to dominate global manufacturing (Li, 2018), and manufacturing has contracted in many parts of the world. Meanwhile, prominent organizations in the maker movement have contracted rather than expanded. Accordingly, the research has been carried out to provide more balance in evaluation of the potential for technological advances to enable sustainable distributed manufacturing.

5.1.1 Main contributions

In particular, three research gaps have been addressed through three research questions related to three trade-offs: product originality, product complexity and product unsustainability versus sustainable distributed manufacturing. These trade-offs are not sector-specific. It has been hypothesised that potential for expansion of sustainable distributed manufacturing will be highest when what is to be produced has low originality, low complexity and high sustainability. By contrast, it can be anticipated that potential for expanision of sustainable distributed manufacturing will be lowest when what is to be produced has high originality, high complexity and low sustainability. As summarized in section 3 of the dissertation and reported in the five papers, main findings from the research are as listed below.

1) Findings reported in Papers I and Paper II indicate that technological advances enable expansion of sustainable distributed manufacturing of original products, if the products are small simple products outside of exclusive bespoke brands, rather than large complicated products.
2) Findings reported in Paper III indicate that technological advances enable sustainable distributed manufacturing of products that are more complex than would otherwise be made far from manufacturing infrastructures, but which nonetheless are not the most complex products.
3) Findings reported in Papers IV and V indicate that technological advances can reduce the trade-off between product unsustainability and sustainable distributed manufacturing if they are applied selectively to improve old manufacturing processes and distributions, alongside enabling new manufacturing processes and distributions.

5.1.2 Supplementary contributions

As described in 4.4. above, three further contributions have arisen from the scope of the research reported in this dissertation. A fourth contribution as summarized in Figure 14 above is as follows:

4) The dissertation makes explicit the constraining influences of the three fundamental trade-offs, which can enable them to be recognized from the outset in debate amongst governments, companies, communities and/or individuals about expanding sustainable manufacturing distributions.

The dissertation brings together research into DIY manufacturing, artisanal manufacturing, and industrial manufacturing: from raw materials processing to product assembly in different sectors. The inclusiveness of the research has revealed the broad relevance of concurrent engineering to improve new, as well as established, distributions of manufacturing. Hence, the fifth contribution from the research is as summarized below.

5) Particularly away from the constraining influence of the three fundamental trade-offs (Figure 14a), concurrent engineering methods can facilitate expanding a wide range of sustainable manufacturing distributions.

Furthermore, the dissertation brings together research encompassing a wide range of digital and physical technologies. The research reveals that particularly, away from the constraining influence of the three trade-offs (Figure 14a), adaptations of established technologies can facilitate sustainable distributed manufacturing. Hence, the sixth contribution from the research is as stated below.

6) Away from the constraining influence of the three fundamental trade-offs (Figure 14a), technological adaptations, such as product kits and moveable factories, can facilitate expansion of sustainable manufacturing distributions.

5.2 Directions for further research

Consideration of the six contributions suggests two strategies for expanding sustainable manfaucturing distributions within the context of inclusive manufacturing: trade-off reduction and trade-off avoidance.

5.2.1 Trade-off reduction strategy

Trade-off reduction strategy for expanding sustainable distributed manufacturing can be stated as follows:

where production needs to be carried out close to the constraining influence of the three fundamental trade-offs, reduce their constraining influence through selective application of technological advances in so far as is technically feasible and is consistent with brand expectations.

One direction for further research is to explore potential to apply the theory of constraints to the management of demand chains and supply chains in sustainable manufacturing distributions. Within the theory of constraints (TOC), any system is limited by a few constraints. Application of TOC involves restructuring the rest of affected organization around the most influential constraint in order to minimise its impact. The relevance of TOC to supply chain management has been recognised for some years (Simtupang et al., 2004). Nonetheless, it provides a novel direction for addressing the constraints of the three fundamental trade-offs in the expansion of sustainable manufacturing distributions.

A related direction for further research is investigate potential for application of information-theoretic entropy (ITE) to describe the extent of constraints arising from the three fundamental trade-offs. For example, ITE has been related to product originality in terms of different customer order decoupling points (Luo et al., 2008). Also, ITE has been related to product complexity in terms of assembly difficulty (Sturges, 1989). In addition, ITE has been related to product unsustainability in terms of product environmental footprint (He et al., 2018). ITE can be related to statistical mechanics (Jaynes, 1957). ITE grows linearly but related entropy in statistical mechanics grows exponentially (Stone, 2015). For example, a linear increase of ITE from 6.00 to 7.00 relates to a doubling of entropy in statistical mechanics from 64.00 to 128.00. This relationship between ITE and statistical mechanics can provide insights into the impact of fundamental trade-offs from design through to product completion. Moreover, it can facilitate comparison of different alternatives for reducing trade-offs in terms of the principle of least action (Feynman, 1942), where the option enabling the least action throughout a manufacturing distribution is the preferable option.

5.2.2 Trade-off avoidance strategy

Trade-off avoidance strategy for expanding sustainable distributed manufacturing can be stated as follows:

if it is not essential for production to be carried out close to the three fundamental trade-offs, then prevent unintended increases in the originality, complexity and unsustainability of what is made through applying concurrent engineering and technological adaptations.

Sustainable manufacturing distributions can be expanded away from the constraining influence of the three trade-offs through scaling up of moveable production (Paper III). This can be done if concurrent engineering and technological adaptations are applied in the development of product kits and the fitting out of moveable factories to reduce production waste (Paper I) and skill barriers (Paper II). For example, through engineering design of product architectures, families of parts, and production equipment including jigs and tools for use across multiple product types. In doing so, it is important to combine the comparative advantages of moveable factories with those of fixed factories (Paper V). In addition, it is important to take up manufacturing process adaptations that can reduce the challenges of expanding manufacturing distributions for versatile components such as metal box sections (Paper IV).

One direction for further research is to investigate to what extent, if any, scaling up moveable production can improve the ecological and social sustainability of "first mile" and "last mile" logistics in industrialized countries (Macioszek, 2018). Another direction for future research is to investigate to what extent, if any, scaling up moveable production can be a more ecologically and socially sustainable option for regions suffering from premature de-industrialization (Rodrik, 2016) than exporting raw materials and importing completed goods. Again, ITE could be applied as a starting point to compare alternative options.

5.2.3 Inclusive manufacturing

The research reported in this dissertation is inclusive of a wide range of manufacturing from raw materials processing to assembly and installation of completed goods. The research included manufacturing in many sectors from large capital goods to small consumer goods; and encompassed distributions of manufacturing from large centralized plants to household DIY. The research encompassed different regions with varying extents of manufacturing infrastructure. Thus, as stated in section 1.1., the research was intentionally inclusive of the diversity of manufacturing in order to facilitate identification of common underlying issues that transcend sectors and borders. Since 2017, there has been an Indian Inclusive Manufacturing Forum. The research reported in this dissertation has led to the author being invited to the steering committee of India's Inclusive Manufacturing Forum (NIAS, 2018). At the outset of this research, there was little interest in Inclusive Manufacturing. By 2018, it was included in the report of the World Manufacturing Forum (WMF, 2018). Accordingly, an appropriate future direction for continuation of the research is investigation of the potential advantages and disadvantages of Inclusive Manufacturing for expanding sustainable manufacturing distributions: away from and close to the three fundamental trade-offs.

In doing so, insights can be drawn from ecology studies. There is already some use of ecology term, ecosystem, in literature related to manufacturing (Reynolds et al., 2018). However, much more of ecology studies could be applied to describe and to facilitate Inclusive Manufacturing. For example, ecology studies provide insights into facilitating diversity through taking measures to improve connectivity between patches across different ecosystems (Saura and Rubio, 2010). Open Source Ecology

(Thomson and Jabubowski, 2012), which is referred to in dissertation Figure 5a, can be described as one of many patches in the open source ecosystem. This patch in the open source ecosystem could be connected to other patches in other not-for-profit ecosystems, such as groups of engineers in diaspora associations (Kuznetsov and Sabel, 2008).

Moreover, reference to ecology studies reveals the importance of both of the two proposed strategies. In particular, long-term sustainability can depend upon flexibility and efficiency. The trade-off reduction strategy is concerned with sustainable expansion of manufacturing that is sufficiently flexible to produce original one-of-a-kind goods. The trade-off avoidance strategy can bring efficiency to manufacturing distributions. Hence, as summarized in Figure 15, expansion of sustainable manufacturing distributions can depend on implementing a balance of both strategies. Again, information-theoretic constructs could be applied to describe the relative potential of alternative options for combining flexibility and efficiency (Kharrazi et al., A. 2013).

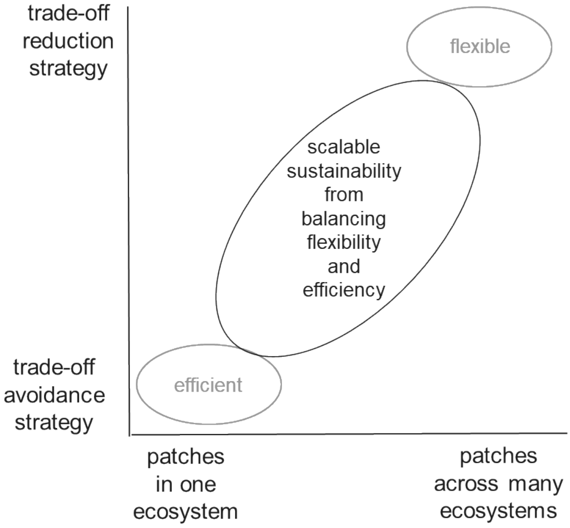


Figure 15. Scalable sustainability from balancing the two trade-off strategies

Overall, drawing upon ecology studies may enable Inclusive Manufacturing to be developed as a coupled human and environment system (Werner & McNamara, 2007), within which greater diversity facilitates more resilient sustainability (Leslie et al., 2013).

6 REFERENCES

Agrawal, M., Kumaresh, T.V., & Mercer, G.A. (2002). The false promise of mass customization. *The McKinsey Quarterly*, 38(3), 62-71.

Amirapu, A., & Subramanian, A. (2014). Manufacturing futures: For India, Reversing the process of de-industrialisation will be hard. *Business Standard*, May 9.

Anderson, C. (2012). *Makers: The new industrial revolution, Crown Business*. New York, NY. Random House Inc.

Anderson, L. W., Krathwohl, D. R., Airasian, P. W., Cruikshank, K. A., Mayer, R. E., Pintrich, P. R., ... & Wittrock, M. C. (2001). A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives, abridged edition. White Plains, NY, USA. *Longman.*

Ayentimi, D. T., & Burgess, J. (2018). Is the fourth industrial revolution relevant to sub-Sahara Africa?. *Technology Analysis & Strategic Management*, 1-12.

Baldwin, R. (2013). Trade and industrialization after globalization's second unbundling: How building and joining a supply chain are different and why it matters. In *Globalization in an age of crisis: Multilateral economic cooperation in the twenty-first century* (pp. 165-212). University of Chicago Press.

Barteková, E., & Kemp, R. (2016). National strategies for securing a stable supply of rare earths in different world regions. *Resources Policy*, *49*, 153-164.

Berg, A., Hedrich, S., Lange, T., Magnus, K., & Mathews, B. (2017). The apparel sourcing caravan's next stop: Digitization. *McKinsey Apparel, Fashion and Luxury Group. September.*

Beverland, M. B., & Farrelly, F. J. (2009). The quest for authenticity in consumption: Consumers' purposive choice of authentic cues to shape experienced outcomes. *Journal of Consumer Research*, *36*(5), 838-856.

Bhaskar, R.A. (1978) *Realistic Theory of Science*. Brighton, UK. *Harvester Press*

Bogue, R. (2014). What future for humans in assembly?. *Assembly Automation*, *34*(4), 305-309.

Bogdanski, S., & Chang, B.C. (2005). Collecting grey literature: An annotated bibliography, with examples from the sciences and technology. *Science & Technology Libraries, 25*(3), 35–70.

Boothroyd, G., Dewhurst, P., and Knight, W.A., (2002) *Product design for manufacture and assembly.* New York, USA. M. Dekker.

Brandon-Jones, E., Dutordoir, M., Neto, J.Q.F., & Squire, B. (2017). The impact of reshoring decisions on shareholder wealth. Journal of Operations Management, 49, 31-36.

Bransford, J.D., Franks, J.J. Vye, N.J. and Sherwood, R.D. (1989). New Approaches to Instruction: Because Wisdom Can't Be Told. In *Similarity and Analogical Reasoning.* S. Vosniadou, Andrew Ortony (eds). New York, Cambridge University Press

Brecher, C., Utsch, P., Klar, R., & Wenzel, C. (2010). Compact design for high precision machine tools. *International Journal of Machine Tools and Manufacture*, *50*(4), 328-334.

Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., ... & Singh, M. (1987). Our Common Future: Oxford University Press.

Bryson, J. R., Mulhall, R. A., Lowe, N., & Stern, J. (2018). Engineering and the Skills Crisis in the UK and USA: A Comparative Analysis of Employer-Engaged Education. In *Value Creation through Engineering Excellence* (pp. 327-349). Palgrave Macmillan, Cham.

Christensen, B., & Brunoe, T.D. (2018). Product Configuration in the ETO and Capital Goods Industry: A Literature Review and Challenges. In *Customization 4.0* (pp. 423-438). Springer, Cham.

Chandler, P., & Sweller, J. (1991). Cognitive load theory and the format of instruction. *Cognition and instruction*, *8*(4), 293-332.

Cook, T.D., & Campbell, D.T. (1979). *Quasi-experimentation: Design and analysis issues for field settings*, Chicago, USA, Rand McNally.

Cutler, T.R. (2005). *Engineer-to-order manufacturers face ERP selection challenges*. Fort Lauderdale, FL, USA, TR Cutler Inc.

Dasgupta, S., & Singh, A. (2006). Manufacturing, services and premature deindustrialization in developing countries: A Kaldorian analysis. *Research Paper, No. 2006/49*. Helsinki, Finland, UNU-WIDER.

Daunfeldt, S. O., Mihaescu, O., Nilsson, H., & Rudholm, N. (2017). What happens when IKEA comes to town?. *Regional studies*, *51*(2), 313-323.

Davenport, T.H., & Prusak, L. (2000). *Working Knowledge: how organizations manage what they know*. Boston, USA, Harvard Business School Press.

Dawidson, O., Karlsson, M., & Trygg, L. (2004). Complexity perception—model development and analysis of two technical platform projects in the mobile phones industry. *International Journal of Information Technology & Decision Making*, *3*(03), 493-512.

Desilver, D. (2017). Most Americans unaware that as US manufacturing jobs have disappeared, output has grown. *Washington, DC: Pew Research Center, July*, *25*.

Eastman, C.M. (Ed.). (2012) *Design for X: Concurrent engineering imperatives*. Springer Science.

Elgh, F. (2012). Decision support in the quotation process of engineered-to-order products. *Advanced Engineering Informatics*, *26*(1), 66-79.

Ellram, L. M., Tate, W. L., & Petersen, K. J. (2013). Offshoring and reshoring: an update on the manufacturing location decision. *Journal of Supply Chain Management*, *49*(2), 14-22.

Fawcett, J., & Downs, F.S. (1986). The Relationship of Theory and Research. Norwalk, CT, USA, *Appleton-Century-Crofts*.

Felipe, J., Kumar, U., Abdon, A., & Bacate, M. (2012). Product complexity and economic development. *Structural Change and Economic Dynamics*, *23*(1), 36-68.

Feynman, R.P. (1942). *The Principle of Least Action in Quantum Mechanics*. Ph.D. Thesis, Princeton University, Princeton, NJ, USA.

Finocchiaro, C. W. (2012). Personal Factory or Catalyst for Piracy: The Hype, Hysteria, and Hard Realities of Consumer 3-D Printing. *Cardozo Arts & Ent. LJ*, *31*, 473.

Flynn, J. M., Shokrani, A., Newman, S. T., & Dhokia, V. (2016). Hybrid additive and subtractive machine tools–Research and industrial developments. *International Journal of Machine Tools and Manufacture*, *101*, 79-101.

Fong, M. W. (2009). Technology leapfrogging for developing countries. In *Encyclopedia of Information Science and Technology*, Second Edition, IGI Global, pp. 3707-3713.

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573-1587.

Fratocchi, L., Ancarani, A., Barbieri, P., Di Mauro, C., Nassimbeni, G., ... & Zanoni, A. (2016). Motivations of manufacturing reshoring: an interpretative framework. *International Journal of Physical Distribution & Logistics Management*, 46(2), 98-127.

Fratocchi, L., Di Mauro, C., Barbieri, P., Nassimbeni, G., & Zanoni, A. (2014). When manufacturing moves back: concepts and questions. *Journal of Purchasing and Supply Management*, *20*(1), 54-59.

Frey, C.B. (2015). Cheap automation raises risk of premature deindustrialisation. *Financial Times*, September 30.

Gavish, N., Gutiérrez, T., Webel, S., Rodríguez, J., Peveri, M., Bockholt, U., & Tecchia, F. (2015). Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. *Interactive Learning Environments*, *23*(6), 778-798.

Gazheli, A., van den Bergh, J., & Antal, M. (2016). How realistic is green growth? Sectoral-level carbon intensity versus productivity. *Journal of Cleaner Production*, *129*, 449-467.

Giffi, C., Wellener, P., Dollar, B., Manolian, H.A., Monck, L. & Moutray, C. (2018). *Deloitte and The Manufacturing Institute skills gap and future of work study report*. Deloitte Development LLC.

Gosling, J., & Naim, M. M. (2009). Engineer-to-order supply chain management: A literature review and research agenda. *International journal of production economics*, *122*(2), 741-754.

Gould, K.A., Pellow, D.N., & Schnaiberg, A. (2015). *Treadmill of production: Injustice and unsustainability in the global economy*. Abingdon, Ox, UK, Routledge.

Grabowski, R. (2017). Premature deindustrialization and inequality. *International Journal of Social Economics*, *44*(2), 154-168.

Gray, J. V., Esenduran, G., Rungtusanatham, M. J., & Skowronski, K. (2017). Why in the world did they reshore? Examining small to medium-sized manufacturer decisions. *Journal of Operations Management*, *49*, 37-51.

Gress, D. R., & Kalafsky, R. V. (2015). Geographies of production in 3D: Theoretical and research implications stemming from additive manufacturing. *Geoforum*, *60*, 43-52.

Grossman, D. (2017). Highly-automated Austrian steel mill only needs 14 people: Don't count on the steel industry to keep supplying jobs. *Popular Mechanics*, June 22.

Guo, L.L., Qu, Y., & Tseng, M. L. (2017). The interaction effects of environmental regulation and technological innovation on regional green growth performance. *Journal of Cleaner Production*, *162*, 894-902.

Hartmann, D., Guevara, M. R., Jara-Figueroa, C., Aristarán, M., & Hidalgo, C. A. (2017). Linking economic complexity, institutions, and income inequality. *World Development*, *93*, 75-93.

Haug, A., Ladeby, K., & Edwards, K. (2009). From engineer-to-order to mass customization. *Management Research News*, *32*(7), 633-644.

Hayes, R.H., & Wheelwright, S.C. (1979). Link manufacturing processes and product life-cycles. *Harvard Business Review*, 57(1), 133-140.

He, B., Xiao, J., & Deng, Z. (2018). Product design evaluation for product environmental footprint. *Journal of Cleaner Production*, 172, 3066-3080.

Hidalgo, C. A., & Hausmann, R. (2009). The building blocks of economic complexity. *Proceedings of the national academy of sciences*, *106*(26), 10570-10575.

Hidalgo, C. A., Klinger, B., Barabási, A. L., & Hausmann, R. (2007). The product space conditions the development of nations. *Science*, *317*(5837), 482-487.

Hoekstra, A. Y. (2015). The sustainability of a single activity, production process or product. *Ecological indicators*, *57*, 82-84.

Hoekstra, A. Y., & Wiedmann, T. O. (2014). Humanity's unsustainable environmental footprint. *Science*, *344*(6188), 1114-1117.

Inman, R. R., & Blumenfeld, D. E. (2014). Product complexity and supply chain design. International Journal of Production Research, 52(7), 1956-1969.

Ioannidis, J.P.A. (2018). Meta-research: Why research on research matters. *PLoS Biology*, 16(3), e2005468.

Ioannidis, J.P.A (2016). Why most clinical research is not useful. *PLoS Medicine*, 13(6), e1002049.

Ioannidis, J.P.A. (2005). Why most published research findings are false. *PLoS Medicine* 2(8): e124.

Jaynes, E.T. (1957). Information theory and statistical mechanics. *Physical Review*, 106(4), 620.

Jiang, P., Leng, J., Ding, K., Gu, P., & Koren, Y. (2016). Social manufacturing as a sustainable paradigm for mass individualization. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, *230*(10), 1961-1968.

Jung, S., & Jin, B. (2016). From quantity to quality: understanding slow fashion consumers for sustainability and consumer education. *International Journal of Consumer Studies*, 40(4), 410-421.

Jokar, A., & Sahraeian, R. (2012). A heuristic based approach to solve a capacitated location-routing problem. *Journal of Management and Sustainability*, 2(2), 219–226.

Josephson, J.R., & Josephson, S.G. (2007). Abductive Inference: Computation, Philosophy, Technology. Cambridge, UK, *Cambridge University Press*.

Jreissat, M., Isaev, S., Moreno, M., & Makatsoris, C. (2017). Consumer driven new product development in future re-distributed models of sustainable production and consumption. *Procedia CIRP*, 63, 698-703.

Juknys, R., Liobikienė, G., & Dagiliūtė, R. (2014). Sustainability of catch-up growth in the extended European Union. *Journal of cleaner production*, *63*, 54-63.

Kahia, M., Kadria, M., Aissa, M. S. B., & Lanouar, C. (2017). Modelling the treatment effect of renewable energy policies on economic growth: Evaluation from MENA countries. *Journal of cleaner production*, *149*, 845-855.

Kate, J., Teunter, R., Kusumastuti, R.D., & van Donk, D.P. (2017). Bio-diesel production using mobile processing units: A case in Indonesia. *Agricultural Systems*, 152, 121-130.

Katic, M., & Agarwal, R. (2018). The Flexibility paradox: Achieving ambidexterity in high-variety, low-volume manufacturing. *Global Journal of Flexible Systems Management*, *19*(1), 69-86.

Kharrazi, A., Rovenskaya, E., Fath, B.D., Yarime, M., Kraines, S. (2013) Quantifying the sustainability of economic resource networks: An ecological information-based approach. *Ecological Economics*, 90, 177-186.

Kiumarsi, B., Vamvoudakis, K. G., Modares, H., & Lewis, F. L. (2018). Optimal and autonomous control using reinforcement learning: A survey. *IEEE transactions on neural networks and learning systems*, *29*(6), 2042-2062.

Kohtala, C. (2015). Addressing sustainability in research on distributed production: an integrated literature review. *Journal of Cleaner Production*, *106*, 654-668.

Kohtala, C., & Hyysalo, S. (2015). Anticipated environmental sustainability of personal fabrication. *Journal of Cleaner Production*, *99*, 333-344.

Korpivaara, V., Elfvengren, K., & Kassi, T. (2014). Improving project manufacturing coordination. *Management and Production Engineering Review*, *5*(3), 33-41.

Kwon, B. R., & Lee, J. (2017). What makes a maker: the motivation for the maker movement in ICT. Information Technology for Development, 23(2), 318-335.

Latter, C., Phau, I., & Marchegiani, C. (2010). The roles of consumers need for uniqueness and status consumption in haute couture luxury brands. *Journal of Global Fashion Marketing*, *1*(4), 206-214.

Leslie, P., McCabe, J.T., Bollig, M., Greiner, C., Fratkin, E., Galaty, J.G., ... & Nelson, F. (2013). Response diversity and resilience in social-ecological systems. *Current Anthropology*, 54(2), 114-143.

Li, L. (2018). China's manufacturing locus in 2025: With a comparison of "Made-in-China 2025" and "Industry 4.0". *Technological Forecasting and Social Change*, *135*, 66-74.

Lindtner, S. (2015). Hacking with Chinese characteristics: The promises of the maker movement against China's manufacturing culture. *Science, Technology, & Human Values*, *40*(5), 854-879.

Little, D., Rollins, R., Peck, M., & Porter, J. K. (2000). Integrated planning and scheduling in the engineer-to-order sector. *International Journal of Computer Integrated Manufacturing*, *13*(6), 545-554.

Longo, F., Nicoletti, L., & Padovano, A. (2017). Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context. *Computers & industrial engineering*, *113*, 144-159.

Luo, J.Q., Han, Y.Q., & Zhou, X. (2008). *Positioning of CODP based on entropy technology and ideal point principle*. In 2008 IEEE 4th International Conference on Wireless Communications, Networking and Mobile Computing, pp. 1-5.

Lyon, T. P., & Montgomery, A. W. (2015). The means and end of greenwash. *Organization & Environment*, *28*(2), 223-249.

Mac, R., 2016. Behind The crash of 3D Robotics, North America's most promising drone company. Forbes. October 5.

Macioszek E. (2018) *First and Last Mile Delivery – Problems and Issues*. In: Sierpiński G. (eds) Advanced Solutions of Transport Systems for Growing Mobility. TSTP 2017. Advances in Intelligent Systems and Computing, vol 631. Springer, Cham.

Maconachie, R., & Hilson, G. (2011, November). Safeguarding livelihoods or exacerbating poverty? Artisanal mining and formalization in West Africa. In *Natural Resources Forum* (Vol. 35, No. 4, pp. 293-303). Oxford, UK: Blackwell Publishing Ltd.

Malone, E. (2017). Mourning the loss of TechShop. *Make Magazine*, November 16.

Mandavilli, A. (2006). Make anything, anywhere. *Nature, 442*, 862-864.

Manufuture High-Level Group (2018). ManuFUTURE—VISION 2030. *Manufuture Implementation Support Group*.

Marshall, J., Rossi, C. (2017). Making with China. *Digital Culture & Society*, 3(1), 127-138.

McCole, Mm (2016). How to make your Philips smart LED bulbs do your bidding. *Wired*, 20 January.

Meyerson, B. (2015). *Emerging Tech 2015: Distributed Manufacturing*. World Economic Forum, March 4.

Miller, J.G., & Roth, A.V. (1994). A taxonomy of manufacturing strategies. *Management Science, 40*(3), 285-304.

Millington, K.A. (2017). How changes in technology and automation will affect the labour market in Africa. Report 041, Brighton, UK, *Institute of Development Studies*.

Mingers, J. (2014). *Systems Thinking, Critical Realism And Philosophy: A Confluence of Ideas*. Abingdon, OX, UK, Routledge.

Mitchell, J. D., Smith, L. J., & Dana, L. P. (2009). The international marketing of New Zealand merino wool: past, present and future. *International Journal of Business and Globalisation*, *3*(2), 111-122.

Moir, W. H., & Mowrer, H. T. (1995). Unsustainability. *Forest Ecology and Management*, *73*(1-3), 239-248.

Modell, S. (2015). Theoretical triangulation and pluralism in accounting research: a critical realist critique. *Accounting, Auditing & Accountability Journal*, 28(7), 1138–1150.

Moradlou, H., & Backhouse, C. J. (2016). A review of manufacturing re-shoring in the context of customer-focused postponement strategies. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 230(9), 1561-1571.

Moreno, M., & Charnley, F. (2016, April). Can re-distributed manufacturing and digital intelligence enable a regenerative economy? An integrative literature review. In *International Conference on Sustainable Design and Manufacturing* (pp. 563-575). Springer, Cham.

Mudambi, R., Saranga, H., & Schotter, A. (2017). Mastering the make-in-India challenge. *MIT Sloan Management Review*, *58*(4), 59-66.

Nam, J. H., Kim, D. H., & Lee, H. J. (2010). An approach to computerized preliminary design procedure of mid-size superyachts from hull modeling to interior space arrangement. *International Journal of Naval Architecture and Ocean Engineering*, *2*(2), 96-103.

NIAS (2018). Inclusive Manufacturing Forum Report 2018. *National Institute of Advanced Studies*, Bangaluru, India.

Niiniluoto, I (2014). Scientific progress as increasing verisimilitude. *Studies in History and Philosophy of Science Part A*, 46, 73-77.

Norton, K. (2006) Savile Row never goes out of style. *BusinessWeek*, October 31.

Olhager, J. (2003). Strategic positioning of the order penetration point. *International journal of production economics*, *85*(3), 319-329.

Omeje, K. D, (Ed). (2008). *Extractive Economies and Conflicts in the Global South: Multi-Regional Perspectives on Rentier Politics*. Farnham, UK, Ashgate Publishing Ltd.

Oqubay, A. (2015). *Made in Africa: Industrial policy in Ethiopia*. Oxford University Press, USA.

Oropallo, W., & Piegl, L. A. (2016). Ten challenges in 3D printing. *Engineering with Computers*, *32*(1), 135-14

O'Sullivan, E. (2018) Excellence in the maker movement. Journal of Peer Production, 3(12), 46-50.

Patton, M. Q. (1991). Towards utility in reviews of multivocal literatures. *Review of Educational Research*, *61*(3), 287-292.

Paavola, S. (2004). Abduction as a logic and methodology of discovery: The importance of strategies. *Foundations of Science*, *9*(3), 267-283.

Pearl, J. (2009) *Causality: Models, Reasoning and Inference* (2nd ed.). New York, NY, USA, Cambridge University Press.

Picard, G. (2016). The 15 best Ikea hacks of all time. *Good Housekeeping*, July 21.

Pilling, D. (2017). Chinese investment in Africa: Beijing's testing ground. *Financial Times*, June 13.

Pohl, R., & Pohl, R. F. (Eds.). (2004). *Cognitive illusions: A handbook on fallacies and biases in thinking, judgement and memory*. Psychology Press.

Porter, M. E. (1998). *Clusters and the new economics of competition* (Vol. 76, No. 6, pp. 77-90). Boston, MA: Harvard Business School Press.

Powell, A. (2012). Democratizing production through open source knowledge: from open software to open hardware. *Media, Culture & Society*, *34*(6), 691-708.

Powney, J., & Watts, M. (1987). *Interviewing in Education Research.* London, UK, Routledge & Kegan Paul.

Puche, J., Ponte, B., Costas, J., Pino, R., & De la Fuente, D. (2016). Systemic approach to supply chain management through the viable system model and the theory of constraints. *Production Planning & Control*, 27(5), 421-430.

Pugh, S. 1991. *Total Design: Integrated Methods for Successful Product Engineering*. Harlow, Essex, UK, Addison Wesley Longman Limited.

Rahman Abdul Rahim, A., & Shariff Nabi Baksh, M. (2003). The need for a new product development framework for engineer-to-order products. *European Journal of Innovation Management*, *6*(3), 182-196.

RamõÂrez-Carrillo, E., LoÂpez-Corona, O., Toledo-Roy, J.C., Lovett, J.C., de LeoÂn-GonzaÂlez, F., Osorio-Olvera, L., et al. (2018) Assessing sustainability in North America's ecosystems using criticality and information theory. *PLoS ONE* 13(7): e0200382.

Rauch, E., Dallinger, M., Dallasega, P., & Matt, D. T. (2015). Sustainability in manufacturing through distributed manufacturing systems (DMS). *Procedia CIRP*, *29*, 544-549.

Reynolds, E.B. & Uygun, Y. (2018) Strengthening advanced manufacturing innovation ecosystems: The case of Massachusetts. *Technological Forecasting and Social Change*, 136, 178-191.

Resta, B., Dotti, S., Pinto, R., Bandinelli, R., Rinaldi, R., & Ciarapica, F. E. (2014). Practices for environmental sustainability in the textile, clothing and leather sectors: The Italian case. *International Journal of Operations and Quantitative Management*, *20*(3), 193-225.

Riti, J. S., Song, D., Shu, Y., & Kamah, M. (2017). Decoupling CO_2 emission and economic growth in China: Is there consistency in estimation results in analyzing environmental Kuznets curve?. *Journal of cleaner production*, *166*, 1448-1461.

Robson, C. (2011). *Real World Research*, 3rd ed., Chicester, UK, John Wiley & Sons Ltd.,

Rodrik, D. (2016). Premature deindustrialization. *Journal of Economic Growth*, *21*(1), 1-33.

Rodrik, D. (2014) The past, present, and future of economic growth. In F. Allen, et al., *Towards a better global economy: Policy Implications for Citizens Worldwide in the 21st Century.* Oxford, UK, Oxford University Press.

Rodrik, D. (2012). Unconditional convergence in manufacturing. *The Quarterly Journal of Economics*, *128*(1), 165-204.

Romli, A., Prickett, P., Setchi, R., & Soe, S. (2015). Integrated eco-design decision-making for sustainable product development. *International Journal of Production Research*, 53(2), 549-571.

Saura, S., & Rubio, L. (2010). A common currency for the different ways in which patches and links can contribute to habitat availability and connectivity in the landscape. *Ecography*, 33(3), 523-537.

Schmidt, S. (2010). The dark side of cloud computing: soaring carbon emissions. *The Guardian*, April 30.

Schwartz, D., Bransford, J., & D. Sears. (2005) Efficiency and innovation in transfer. In J. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective*. CT, USA, Information Age Publishing.

Seccatore, J., Veiga, M., Origliasso, C., Marin, T., & De Tomi, G. (2014). An estimation of the artisanal small-scale production of gold in the world. *Science of the Total Environment*, *496*, 662-667.

Sender, M. (2017). Lack of local parts hampers Make in India campaign. *Financial Times*, April 18.

Seuring, S., & Müller, M. (2008). From a literature review to a conceptual framework for sustainable supply chain management. *Journal of cleaner production*, *16*(15), 1699-1710.

Shun-Shin, M. J., Francis, D. P. (2013). Why even more clinical research studies may be false: effect of asymmetrical handling of clinically unexpected values. *PLoS One*, 8(6), e65323.

Sjøbakk, B., Thomassen, M. K., & Alfnes, E. (2014). Implications of automation in engineer-to-order production: a case study. *Advances in Manufacturing*, *2*(2), 141-149.

Smith, P. (2009). A Suit That Fits is cutting its cloth to profit from recession. *The Telegraph*, January 6.

Spangenberg, J. H. (2010). The growth discourse, growth policy and sustainable development: Two thought experiments. *Journal of Cleaner Production*, *18*(6), 561-566.

Squire, B., Brown, S., Readman, J., & Bessant, J. (2006). The impact of mass customisation on manufacturing trade-offs. *Production and Operations Management*, 15(1), 10-21.

Stacey, K., & Nicolaou, A. (2017). Stitched up by robots: the threat to emerging economies. *Financial Times*, July 18.

Stangler, D., & Maxwell, K. (2012). DIY producer society. *Innovations: Technology, Governance, Globalization*, *7*(3), 3-10.

Star, S.L. (1989). The structure of ill-structured solutions: Boundary objects and heterogeneous distributed problem solving. In Gasser, L. & Huhns, M.N. (eds) *Distributed Artificial Intelligence*, Morgan Kaufmann. pp. 37-54.

Stegen, K. S. (2015). Heavy rare earths, permanent magnets, and renewable energies: An imminent crisis. *Energy Policy*, *79*, 1-8.

Stjepandić, J., Wognum, N., & Verhagen, W. J. (2015). *Concurrent engineering in the 21st century: Foundations, developments and challenges*. Springer.

Stone, J.V. (2015). *Information Theory: A Tutorial Introduction*, Sebtel Press, Sheffield, UK.

Sturges Jr, R.H. (1989). A quantification of manual dexterity: the design for an assembly calculator, Robotics and Computer Integrated Manufacturing, 6(3) 237–252.

Tanenbaum, J. G., Williams, A. M., Desjardins, A., & Tanenbaum, K. (2013). Democratizing technology: pleasure, utility and expressiveness in DIY and maker practice. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2603-2612). ACM.

Thomson, C.C. and Jakubowski, M. (2012). Toward an open source civilization (Innovations case narrative: Open source ecology). *Innovations: Technology, Governance, Globalization*, 7(3), 53-70.

Tian, J., Shen, L., & Chen, Y. (2017). A study on customer prosumption concept and its impact on enterprise value co-creation. *Economics Letters*, *7*, 2040-2053.

Tsarouchi, P., Matthaiakis, A. S., Makris, S., & Chryssolouris, G. (2017). On a human-robot collaboration in an assembly cell. *International Journal of Computer Integrated Manufacturing*, *30*(6), 580-589.

Tu, Y. (1997). Production planning and control in a virtual one-of-a-kind production company. *Computers in Industry*, *34*(3), 271-283.

Uhlmann, E., Kersting, R., Klein, T. B., Cruz, M. F., & Borille, A. V. (2015). Additive manufacturing of titanium alloy for aircraft components. *Procedia CIRP*, *35*, 55-60.

Ulrich, K.T., & Eppinger, S.D. (2000). *Product Design and Development.* NY, USA, McGraw-Hill Education.

Vanchan, V., Mulhall, R., & Bryson, J. (2018). Repatriation or reshoring of manufacturing to the US and UK. *Growth and Change*, 49(1), 97-121.

Vecchi, A. (ed.) (2017). *Reshoring of Manufacturing: Drivers, Opportunities, and Challenges*. Springer, Cham, Switzerland.

Yu, Y., Han, X., & Hu, G. (2016). Optimal production for manufacturers considering consumer environmental awareness and green subsidies. International Journal of Production Economics, 182, 397-408.

Vonderembse, M.A., & White, G.P. (2007). *Operations Management: Concepts, Methods, and Strategies.* Chicester, UK, John Wiley & Sons Ltd.

Webel, S., Bockholt, U., Engelke, T., Gavish, N., Olbrich, M., & Preusche, C. (2013). An augmented reality training platform for assembly and maintenance skills. *Robotics and Autonomous Systems*, *61*(4), 398-403.

Wenger, E. (1998). Communities of Practice: Learning, Meaning, and Identity. Cambridge: Cambridge University Press.

Werner, B.T; McNamara, D.E (2007). Dynamics of coupled human-landscape systems. *Geomorphology* 91 (3–4): 393–407.

Wikner, J., & Rudberg, M. (2005). Integrating production and engineering perspectives on the customer order decoupling point. *International Journal of Operations & Production Management*, *25*(7), 623-641.

Williamson, M. (2003). Out of this world. *Engineering Management*, *13*(4), 26 -31.

Willner, O., Powell, D., Gerschberger, M., & Schönsleben, P. (2016). Exploring the archetypes of engineer-to-order: an empirical analysis. *International Journal of Operations & Production Management*, *36*(3), 242-264.

Wolf-Powers, L., Doussard, M., Schrock, G., Heying, C., Eisenburger, M., & Marotta, S. (2017). The maker movement and urban economic development. *Journal of the American planning association*, *83*(4), 365-376.

WMF (2018). Recommendations for The Future of Manufacturing 2018. *World Manufacturing Forum Report*

Xu, X. (2012). From cloud computing to cloud manufacturing. *Robotics and computer-integrated manufacturing*, *28*(1), 75-86.

Yang, L. R. (2013). Key practices, manufacturing capability and attainment of manufacturing goals: The perspective of project/engineer-to-order manufacturing. *International Journal of Project Management*, *31*(1), 109-125.

Yang, S., Santoro, F., Sulthan, M. A., & Zhao, Y. F. (2019). A numerical-based part consolidation candidate detection approach with modularization considerations. *Research in Engineering Design*, *30*(1), 63-83.

Yang, L., Wang, J., & Shi, J. (2017). Can China meet its 2020 economic growth and carbon emissions reduction targets?. *Journal of Cleaner Production*, *142*, 993-1001.

Zeuner, B. (2018). An obsolescing bargain in a rentier state: Multinationals, artisanal miners, and cobalt in the Democratic Republic of Congo. *Frontiers in Energy Research*, *6*, 123.

Zhao, X., Sum, C. C., Qi, Y., Zhang, H., & Lee, T. S. (2006). A taxonomy of manufacturing strategies in China. *Journal of Operations Management*, *24*(5), 621-636.

Yin, R.K. (2011). *Applications of case study research*. Thousand Oaks, CA: Sage Publications Inc.

Yizengaw, J.Y. (2018). Skills Gaps and Mismatches: Private Sector Expectations of Engineering Graduates in Ethiopia. Institute of Development Studies, Brighton, UK, *IDS Bulletin*, 49(5).

Zalasiewicz, J., Williams, M., Waters, C. N., Barnosky, A. D., Palmesino, J., Rönnskog, A. S., ... & Grinevald, J. (2017). Scale and diversity of the physical technosphere: A geological perspective. *The Anthropocene Review*, *4*(1), 9-22.

7 PAPERS

PUBLICATION
I

Potential of virtual-social-physical convergence for project manufacturing

Stephen Fox

Journal of Manufacturing Technology Management, 25(8), 1209-1223
https://doi.org/10.1108/JMTM-01-2013-0008)

Fox, S. (2014) Potential of virtual-social-physical convergence for project manufacturing. Journal of Manufacturing Technology Management, 25(8), 1209-1223.

Abstract

Purpose – The purpose of this paper is to provide an analysis of how virtual-social-physical (VSP) convergence can affect different types of project manufacturing. In particular, VSP convergence that involves combining the read-write functionality of Web 2.0 and related social media together with digital tools for virtual design and for physical manufacturing.

Design/methodology/approach – Literature review and interviews with experts in technologies covering VSP convergence: digital data capture, photogrammetry, generative computation, Web 2.0 and social media, digitally-driven manufacturing.

Findings – VSP convergence can enable the replacement of slow and expensive traditional project manufacturing practices with much faster and less expensive digitally-driven technologies.

Practical implications – There are new opportunities for expansion of some types of project manufacturing. Notably, there are opportunities in non-industrial developing countries because VSP convergence reduces reliance on industrial infrastructure for manufacturing. By contrast, opportunities may be limited for expansion of established project manufacturing companies with exclusive brands.

Originality/value – The originality is that VSP convergence is related to different types of project manufacturing. Based on VSP convergence, traditional types and new types of project manufacturing are categorized together for the first time. The value of this paper is that it is explained how VSP convergence can address barriers to expansion of different types of project manufacturing.

Keywords – project manufacturing; virtual-social-physical convergence; mass imagineering; bespoke; engineer-to-order; do-it-yourself (DIY); do-it-with-others (DIWO)

Paper type – Technical paper

Potential of virtual–social-physical convergence for project manufacturing

Introduction

The outputs of project manufacturing are unique original goods. Those are goods which are made only once and arise from the imagination of the customers for whom, or by whom, they are produced. A traditional type of project manufacturing for smaller goods is the bespoke hand-crafting of clothes, jewellery, etc. A traditional type of project manufacturing for larger goods is the engineering-to-order (ETO) of, for example, ocean-going ships. (Hayes and Wheelwright, 1979; Vonderembse and White, 2007). More recent project manufacturing involves companies enabling do-it-yourself (DIY) manufacturing of smaller goods, and do-it-with-others (DIWO) manufacturing of larger goods (Anderson, 2012; Fox, 2013).

In this paper, it is explained how virtual-social-physical (VSP) convergence can affect barriers to expansion of different types of project manufacturing. Technological convergence involves technological innovations from one sector changing production and/or products across other sectors (Bohlin et al. 2000; Brand 1987; Duysters and Hagedoorn 1998; Farber and Baran, 1977; Martin 1978; Von Tunzelmann, 1995). In recent years, information technologies have enabled convergence of the virtual, the social, and the physical (Rheingold, 2002). This VSP convergence adds the read-write functionality of Web 2.0 and associated social media, such as blogs, forums, and wikis, to the previously anticipated convergence of the virtual and the physical (Fox, 2012; Guth, 2007; Kaplan and Haenlein, 2010; Milgram and Kishino, 1994).

First, barriers to expansion of project manufacturing are described. Then, an analysis is provided of how VSP convergence can address barriers to expansion to project manufacturing. Next, the potential of VSP convergence is related to different types of project manufacturing. In the penultimate section, challenges for implementation are described.

Fox, S. (2014) Potential of virtual-social-physical convergence for project manufacturing. Journal of Manufacturing Technology Management, 25(8), 1209-1223.

Challenges are considered as technical issues, micro-economic level issues, and macro-economic level issues. In conclusion, the principal findings of the research are stated.

The research comprised literature review and unstructured interviews with ten experts. The informant style of unstructured interview was used. Hence, the interviewer did not seek to control the interviews. Rather, interviewees freely expressed their thoughts and took the interviews in the direction that they chose. This type of unstructured interview can be contrasted with the respondent style of unstructured interview where the interviewer seeks to follow a more defined agenda (Powney and Watts, 1987). The interviewees comprised a purposive sample of experts (Kuzel, 1999; Patton, 2002) in technologies covering VSP convergence: digital data capture, photogrammetry, generative computation, Web 2.0 and social media, digitally-driven manufacturing. The interviews covered the technological state-of-art, and potential for future progress beyond the state-of-the-art. During interviews, technology demonstrations and manufacturing samples were provided.

The information about technologies provided by interviewees was subsequently related to stages of project manufacturing: data capture, data conversion, design, manufacture, and assembly. For example, data capture in project manufacturing can often involve manual one dimensional measurements that have to be converted into three dimensional representations (Fox et al., 2009; Norton, 2006). The potential of technologies to improve upon this was apparent from the information provided. For example, experts demonstrated the potential of digital cameras and digital scanners to capture data in three dimensions, which could then be converted to 3D digital models by photogrammetry (Luhmann, 2010). Findings from interviews are reported in the analysis of how VSP convergence can address barriers to expansion and in the description of challenges for implementation.

Initial literature review encompassed project manufacturing; technological convergence; and VSP convergence. Subsequent to interviews, literature review was focused upon technical issues, micro-economic level issues, and macro-economic level issues related to the potential of VSP convergence for project manufacturing.

Four contributions to the literature are provided. Firstly, traditional and new types of project manufacturing are categorized together for the first time. Secondly, it is explained how VSP convergence can address barriers to expansion of project manufacturing. Thirdly, comparative opportunities are described for different types of project manufacturing. Fourthly, implementation challenges are discussed.

Barriers to expansion of project manufacturing

The underlying barrier to expansion of project manufacturing is uncertainty. This arises from project produced goods being first seen in the mind's eye of the individual customers who imagine their form and function. As a result, project manufacturing businesses have to wait to find out what each individual customer has in mind before starting design and production. This inherent uncertainty has prevented adoption of many technologies for reducing the time and cost of manufacturing, which have been developed within mass production / mass customization.

For example, the formulation of Bills of Materials and efficient deployment of Manufacturing Resource Planning (MRP) systems is not technically feasible when there is design uncertainty for future orders. Further, Bills of Materials and MRP systems are not economically viable when there is little, or no, repetition of designs. Accordingly, original drawings, estimates, purchase orders and works orders are often prepared for each order in project manufacturing. In addition, automation is seldom technically feasible for project manufacturing because they do not know, from one order to the next, the exact geometry and dimensions of major components. Hence, it is not technically feasible to have tooling, such as moulds, dies, etc. for automated manufacture and assembly. Automation has seldom been economically viable for project manufacturing. This is because when the exact geometry and dimensions of major components for an order are known, those forms are seldom repeated in future orders (Fox et al., 2009).

By contrast, companies operating mass production or mass customization have design certainty for future orders. This is achieved by pre-designing complete goods (i.e. mass production) or pre-designing the sub-assemblies of the goods and pre-defining all the possible configurations of those sub-assemblies as complete goods (i.e. mass customization). This pre-design and pre-definition of goods is aligned with what the marketing departments of mass companies determine to be the common attributes of millions of consumers. Then, mass companies communicate the range of their goods' forms and functions to consumers through mass advertising, in-store displays, online configurators, etc. Hence, it is both technically feasible and economically viable for them to formulate Bills of Materials; to deploy MRP systems; and to automate with manufacturing presses, assembly robotics, etc. The high costs of these mass production / mass customization technologies are then spread across mass sales. Overall, mass producers / mass customizers reduce the time and cost of creating goods by reducing reliance on slow and expensive time-consuming labour-intensive traditional practices. The different outcomes from companies pre-designing goods (better manufacturing efficiency) and individual customers imagining goods (worse manufacturing efficiency) are summarized in Figure 1.

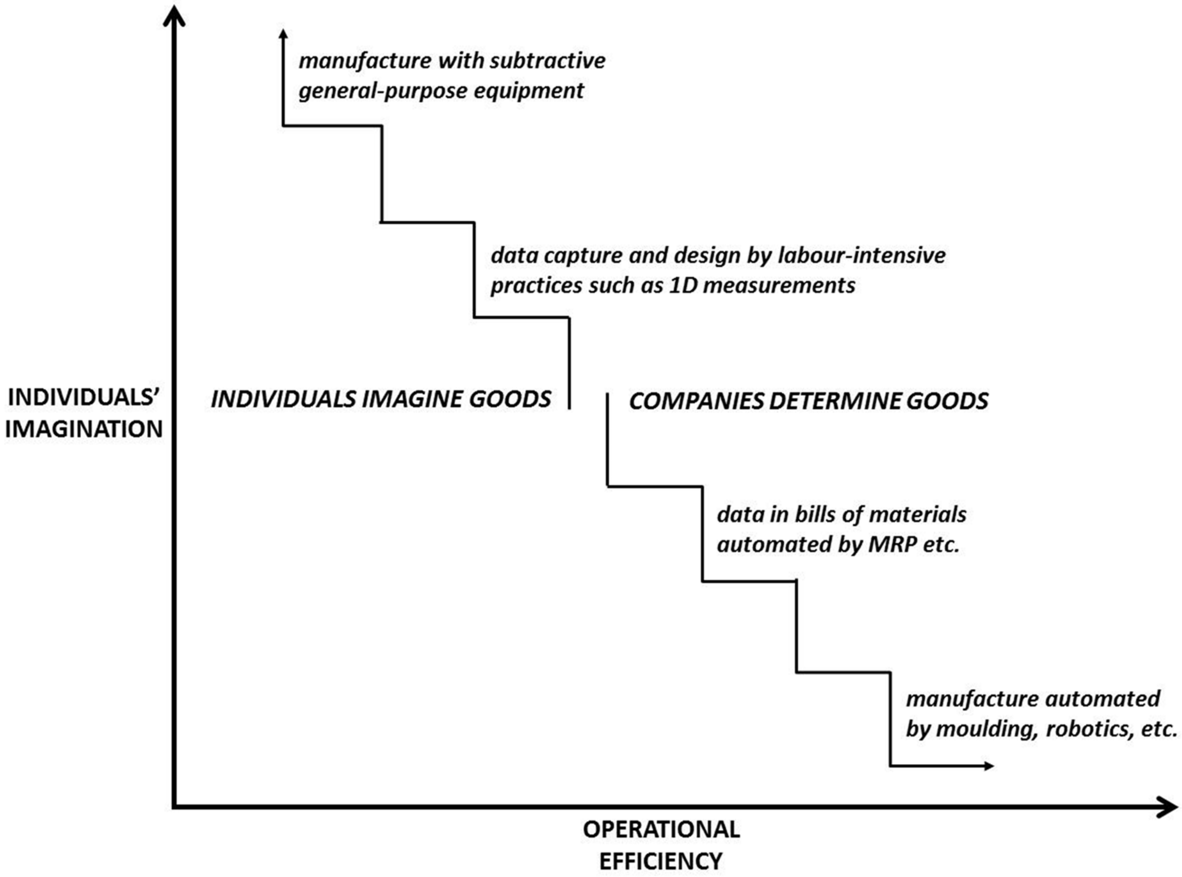


Figure 1: Individuals' imagination versus operational efficiency

In particular, traditional bespoke businesses and ETO enterprises suffer from relatively low productivity because they have continued to rely on slow and expensive time-consuming labour-intensive traditional practices for the multiple iterations of dialogues, measurements, sketches, models, fittings, fixings, etc., that convert an individual's idea into an original physical good. This involves, for example, arcane practices such as preparing three dimensional (3D) drawings from sets of one dimensional (1D) measurements made with tape measures, vernier gauges, etc. Often, it can involve human transposition of information of 3D drawings into alpha numeric data for manufacturing and assembly operations. Thereafter, general-purpose subtractive equipment such as drills, lathes, saws are used to shape materials into components for assembly by hand. Individuals can continue to exercise their imaginations throughout design, manufacture, and assembly as they may have new ideas about details as the work progresses. Subsequently, all of the costs of design and manufacture have to be borne by the price of the one original good that is created.

Accordingly, expansion of project manufacturing requires technological innovations that are much more efficient, but that do not depend upon pre-design of sub-assemblies and the pre-definition of their potential configurations.

Potential for VSP convergence to address barriers

Within VSP convergence, different technologies are brought together to create new opportunities for simplifying the project manufacturing of unique original goods. For example, new DIY / DIWO companies are already bringing together three dimensional (3D) solid modelling software (virtual), Web 2.0 functionality of the Internet in form of blogs plus links to Facebook, Twitter, YouTube (social), and digitally-driven manufacturing (physical) (Dahl, 2012). This VSP convergence extends to the simplification of project manufacturing of original goods with unique micro-electronic functionality. For example, micro-electronics board (physical), Web 2.0 functionality of the Internet in form of blog, forum, wiki plus links to Twitter (social), and micro-electronics programming (virtual) (Sterling, 2011).

In addition, there are other technologies that project manufacturing business can implement to increase VSP convergence and reduce barriers to business expansion. For example, digital photographs, digital videos, and digital scans can be automatically converted into three dimensional virtual models through photogrammetry software. These virtual technologies for data capture and data conversion can radically reduce reliance on arcane practices, which are still used to prepare three dimensional (3D) drawings from sets of one dimensional (1D) measurements made with tape measures, vernier gauges, etc. They can also reduce reliance on tasks that are traditionally needed to convert drawings into alpha numeric data for manufacturing and assembly operations. This is important as many project produced goods are needed to interface with existing goods and environments: for example, to enable refurbishment of machinery. Also, project produced goods, such as assistive devices and prosthetic limbs, are needed to interface with the unique and complicated measurements of the human body (Li et al., 2011; Luhmann, 2010)

Further, there are many new virtual technologies that reduce reliance on CAD skills to represent an idea for an original good as a digital design. For example, rough approximations of a form imagined in the mind's eye, such as physical models shaped from paper, card, etc., can be scanned and converted into 3D virtual models. Also, digital pens enable rough sketches to be drawn on paper and other surfaces to be rapidly converted into digital computer models (Song et al., 2009). Furthermore, many new CAD tools have intuitive user interfaces that are specifically developed for use by people without design training (Parks, 2012).

Then, if project manufacturing should involve a large number of people and should be congruent with the aesthetic preferences of local cultures, languages of design can be formulated by user communities. This extends the read/write functionality of Web 2.0 from social authoring of text, in for example wikis, to social authority of designs for physical goods. Languages of design can be linked to criteria and processes for production and assembly (Fox, 2011). Generative computation can be applied to languages of design. Generative computation automates the evolution of an infinite variety of designs. Generative computations can emulate what human designers/engineers do when they draw, erase, modify and/or move shapes such as lines and curves (Krish, 2011).

With regard to the assembly of manufactured components, generative computations can enable designs to be produced in different sizes using different types of equipment – from the same file. First, this offers the possibility of manufacturing scale models for the purpose of learning how to put the components together to make the full-sized goods. Second, full-sized components can then be produced for assembly into full-sized goods. Also, the components produced for the both the scale model and the complete good can have accurate friction-fit/snap-fit joints, which can be numbered to aid matching. Thus, the need for prior skill knowledge of assembly work is greatly reduced (Sass, 2007).

A summary is provided in Figure 2 of how new virtual, social, and physical manufacturing technologies converge together holistically to enable the traditional trade-off to be overcome between individuals' creativity versus manufacturing efficiency.

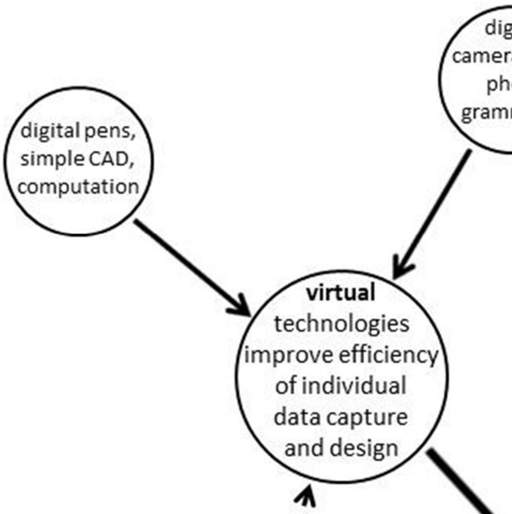


Figure 2: Virtual, social, physical convergence for project manufacturing

Overall, the combination of virtual, social, and physical technologies throughout the manufacturing process can enable reductions in times and costs. This is achieved by replacing slow and expensive time-consuming labour-intensive traditional practices with faster and less expensive digitally-driven technologies. This includes the introduction of low cost and high performance manufacturing equipment (Anderson, 2012) by equipment developers /

vendors, such as MakerBot, Mebotics, and ShopBot (Baraniuk, 2013). Thus as illustrated in Figure 3, project produced goods can become much more competitive with mass produced / mass custom goods while still enabling individuals to exercise their imaginations throughout design, production, and assembly.

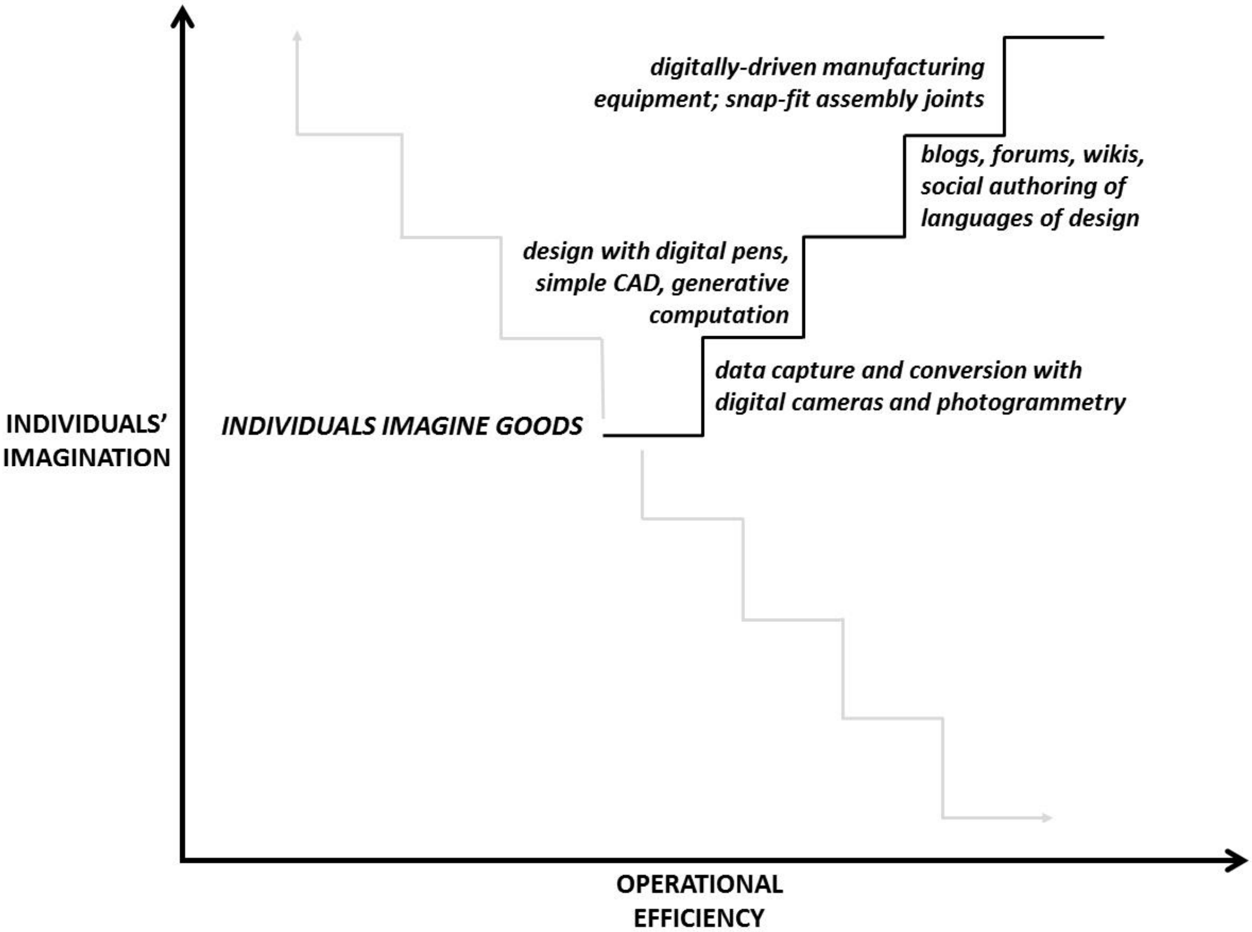


Figure 3: Potential of VSP convergence to transcend traditional trade-off

Potential for expansion of different types of project manufacturing

Bespoke and Engineer-to-Order

Virtual-social-physical (VSP) convergence is well suited to enabling expansion of bespoke manufacturing. This is because bespoke goods are typically small and comprise few components. As a result, they are well-suited to digital manufacturing with technologies such as scanners to capture measurements, photogrammetry, simple CAD tools, and digitally-driven manufacturing. In addition, inviting potential customers to formulate languages of design could expand customer base. Overall, the reductions to time and cost offered by VSP convergence can make bespoke consumer goods much more competitive with mass produced / mass custom goods. Further, VSP convergence can enable a new bespoke business to establish a global brand very quickly. For example, the company Bespoke Innovations makes uniquely beautiful casings, which calls fairings, for standard prosthetics. These fairings are unique to the owner and have a beauty that they treasure, such as a particular geometry which matches their favourite motorcycle. Bespoke Innovations deploys body scanning, online virtual design tool, additive manufacturing, and social media including Facebook and Twitter (Vance, 2012).

Also, many of the internal fixtures for large engineer-to-order (ETO) goods are relatively small, produced by bespoke businesses, and are suited to harnessing the potential of VSP convergence: both during the manufacturing of ETO goods and during their refurbishment. By contrast, ETO goods themselves are often very large. In many cases, large structural frameworks of heavy steel sections have to be erected and fixed together from temporary structures such as scaffolding. Hence compared to bespoke goods, large ETO structures are less suited to, for example, the relatively small manufacturing beds of additive manufacturing machines and computer-numerically controlled milling machines. Further, large ETO structures, such as ocean-going ships, can be subject to extreme dynamic forces, and structural failures can lead to fatal accidents. Thus, although ETO goods can have potentially large communities with interest in the forms and finishes of design, it may not be possible to involve them in, for example, the social authoring of languages of design due to legal ramifications. On the other hand, the knowledge sharing and knowledge evolution offered by Web 2.0 and associated social media could facilitate consensus building among stakeholder groups during detailed design, and later phases of the manufacturing process: especially if augmented with virtual models and physical models within Augmented Reality and Augmented Virtuality

---

Fox, S. (2014) Potential of virtual-social-physical convergence for project manufacturing. Journal of Manufacturing Technology Management, 25(8), 1209-1223.

(Billinghurst and Kato, 2002). Such applications of VSP convergence, however, may have little potential to bring about major reductions in overall times and costs that could increase demand and enable expansion of large-scale ETO manufacturing.

DIY / DIWO

There are significant opportunities for expansion of VSP-enabled DIY / DIWO businesses. Firstly, as more and more non-industrialized developing countries come online, there are more and more opportunities to introduce VSP-enabled DIY / DIWO project businesses (Smith, 2008). This is not least because of absence of existing industrial infrastructure. Consider, for example, the statement of the president of Rwanda: In Africa, we have missed both the agricultural and industrial revolutions, and we are determined to take full advantage of the digital revolution (Kircher-Allen, 2009). The absence of existing industrial infrastructure enables developing countries to skip the centralised industrial paradigms that have evolved in developed countries since the Industrial Revolution. This is similar to developing countries going straight to mobile telecommunications and mobile banking; thus skipping over the fixed infrastructures that have evolved in industrialized countries.

In particular, VSP-enabled DIY / DIWO businesses that can overcome dependency on existing design, production, assembly skills can address the enduring problem of international development projects failing to involve local people in, for example, design and assembly work (Moyo, 2010). This can lead to situations where under employed local populations see foreigners doing work in their countries. This can result in the local populations not caring about what projects are intended to bring to their communities. For example, local populations may even disassemble completed projects so they can take possession of source materials (Dichter, 2003).

DIY / DIWO project manufacturing can be extended to mechanical goods by deploying Body on a Frame structures. These use an internal space frame to carry loads. External non-load bearing panels are attached to the internal frame to keep out wind, rain, etc, and to provide car body shape (Fox and Li, 2012). In addition to creating more individual body panels, new digitally-driven manufacturing technologies can be deployed to enhance cars with unique features such as original additive manufactured handles, mirrors etc. Such components could be widely used in combination with standard sub-assemblies, such as engines, to create original goods. This strategy is already being applied with commercial success by the innovative DIY / DIWO car company, Local Motors (Mone, 2010).

Importantly, procedures to address potential problems in collective decision-making and the distribution of gains have already been implemented successfully by new DIY/DIWO companies (Ordanini et al., 2011; McKeough, 2011).

Challenges for VSP convergence implementation

Technical issues

It is not the purpose of this paper to imply that the technologies referred to are any easier to implement, and are any more reliable in use, than other manufacturing technologies. Rather, as with any manufacturing technologies, each particular potential implementation requires feasibility study and careful planning. For example, any Web-enabled system could crash. Further, any digitally-driven subtractive manufacturing machine could mis-cut occasionally, and any digitally-driven additive manufacturing machine could deposit material incorrectly occasionally. Furthermore, generative computations will certainly generate some designs that are inappropriate and/or very difficult to manufacture – as will human designers.

Nonetheless, all of the technologies referred to in this paper can be used and are undergoing continual improvement. For example, it has been possible to go online, create something using an additive manufacturing 3D printer only to find that it is not strong enough to survive shipping and arrives broken in more than one piece. Accordingly, a program that automatically imparts strength to objects before they are printed has been developed (Stava et al., 2012). More broadly, data compression and data interchange is continual being improved. For example, ASTM F2915 – 12 Standard Specification for Additive Manufacturing File Format (AMF) has been developed (ASTM, 2012).

With regard to physical manufacturing, making larger components, such as vehicle body panels, is more challenging than making smaller components that are within the size range of typical additive manufacturing machines. However, body panels with original unique geometries can be made from, for example, carbon fibre composites, rather than the steels used in mass produced / mass custom cars. This move away from industrial metals is necessary because very strong solid equipment is needed to enable the shaping of strong solid materials, such as high strength steel bars and sheets, into strong solid steel car body panels. This equipment includes sets of huge mechanical presses, as well as very large convex and concave moulds. Such component-specific tooling requires capital investment, which can only be recovered through the sale of tens of thousands of body panels with identical geometries. By contrast, manufacturing materials that are not so strong individually, such as liquid resins, or more flexible, such as carbon fibres, do not require such strong or solid equipment for their shaping into strong solid composite car body panels. This opens up possibilities for reducing the investment costs and environment costs from manufacturing at the same time as creating car bodies that are more individual to their owners (Fox and Li, 2012).

Micro-economic level issues

An important issue in microeconomics is the behaviour of individual firms in making decisions about the quantities and prices of goods and services that they supply. Typically, the supply of project manufactured goods has been much lower than mass produced goods, while the price of project manufactured goods has been much higher. As described above, this has been due to the time-consuming labour-intensive practices involved in project manufacturing. However, although VSP convergence can enable project manufacturing firms to increase supply and lower prices, it may be counterproductive for them to do so within their establish brand identities.

Consider, for example, bespoke businesses that are based at exclusive locations and offer project manufacturing of exclusive goods. These include those based at exclusive London locations, such as Bond Street's bespoke jewellers; Jermyn Street's bespoke shirtmakers; Saville Row's bespoke tailors. Such bespoke businesses can have spent many decades developing their exclusive brand identities, and risk brand dilution if they introduce technologies that are not congruent with that brand identity (Dwivedi et al., 2010; Farquhar, 1989). In particular, brand exclusivity can limit the relevance of the read-write functionality of social media. Hence, exclusive bespoke businesses deploy the Internet for read only and for customer transactions. Furthermore, traditional iterations of dialogues, measurements, fitting and fixings are essential elements of their exclusiveness. Accordingly, the introduction of body scanners, generative computation, digitally-driven manufacturing etc., could undermine an exclusive brand identity. For example, the bespoke tailor occupying Number One Saville Row highlights its craft practices, such as hand sewing, in its marketing (Norton, 2006).

However, not adopting VSP convergence could leave established project manufacturing companies vulnerable to changing perceptions of the relationship between price and quality. Often high prices are associated with high quality (Knauth, 1949; Nagle and Holden, 2002; Rao and Monroe, 1989). However, perceptions of acceptable price ranges for high quality can shift downwards if it becomes evident to customers that the same goods could be produced to the same quality much more quickly and at much lower price (Harmon et al., 2007; Stoetzel, 1970; Van Westendorp, 1976). If project manufacturing companies wait to see whether perceptions of acceptable prices ranges shift downwards before implementing VSP, they may lose established customers and not be able to attract new customers as a result of being late adopters (Everett, 1962). This can happen in only a few months when new companies can rapidly attract customers via the Internet. Indeed, before making any profits, new Internet companies can develop powerful new brands that draw customers away from established companies (Hansell, 2006; Rusli, 2012). Thus, a challenge for project manufacturing companies is determining whether to deal with the potential technical issues of being early adopters or to deal with the potential market difficulties of being late adopters.

When deciding the timing of adopting VSP technologies, firms also need to consider the motivation of their highly skilled workforces. Often project manufacturing is carried out by personnel who have served apprenticeships or other types of long-term structured training with its historic origins in craft guilds. Subsequently, project manufacturing personnel, such as master tailors and master welders, have much wider range of authority and tasks than mass production factory operatives. As a result, the introduction of VSP convergence technologies could demotivate project manufacturing personnel if their tasks and authority become less broad. Such demotivation could partially counteract potential improvements to manufacturing efficiency (Steers and Porte, 1991). Accordingly, careful work design is needed in the implementation of VSP technologies.

Macro-economic level issues

Macroeconomics deals with the performance of an economy as a whole. Many countries that have previously off-shored manufacturing are now seeking to “rebalance” their economies by revitalizing manufacturing (The Economist, 2011). Further, many countries are placing increased emphasis on the potential of creative sectors to contribute to their economic growth (Howkins, 2001; Florida, 2002). Project manufactured goods are creative goods because they arise from the creative imagination of individuals. Now, because of VSP technologies, project produced goods need no longer be labour-intensive goods. Hence, the cost of labour need not be a determining factor in their price. As a result, project manufactured goods can be made cost-effectively in countries that previously off-shored manufactured to other countries with much lower labour costs. Accordingly, project manufacturing with VSP technologies can contribute to macro-economic goals.

However, the availability of VSP convergence technologies is not sufficient to enable their successful implementation in all of the different industrial sectors where project manufacturing businesses operate. This is because knowledge development and sharing is often challenging across project businesses (Hawk and Artto, 1999; Prencipe and Tell, 2001). For example, the different types of project manufacturing are currently not strongly associated by industrial sector categorization or consumer demand categorization. Rather, bespoke manufacturing is associated with sectors such as apparel and furniture, while ETO is associated with sectors such as shipping. Further, DIY / DIWO is commonly associated with the large scale home improvement retail stores that have large physical presence, than with the new Internet-based DIY / DIWO businesses that have distributed digital presence.

Hence, knowledge development and sharing could be better facilitated by a common categorization for project manufacturing, such as mass imagineering. Common to both traditional and recent types of project manufacturing is imagineering. This is a portmanteau word combining imagination and engineering (Time, 1942; Wright, 2005). Imagineering is common to all project produced goods because they are first seen in the mind's eye of the individual customers who imagines their forms and functions. Such a shared categorization could, for example, lead to higher prioritization of project manufacturing in regional, national, and international funding programmes for research and development.

A summary of the different opportunities and challenges for different types of project manufacturing is provided in Table 1. This highlights that VSP convergence may offer limited potential for expansion of established exclusive bespoke businesses, and ETO enterprises for large structures such as ocean-going ships. By contrast, there can be international potential for expansion of other bespoke businesses and DIY / DIWO business.

Table 1: Opportunities for expanding project manufacturing business through VSP convergence

Type	Opportunities for expansion	Challenges to expansion
Traditional	VSP convergence is well suited to enabling expansion of manufacturing of bespoke goods because they are typically small and comprise few components. Similarly, bespoke components for large ETO goods such as ships can be made in less time and at lower cost	Branding, pricing and workforce challenges, especially for exclusive bespoke businesses Limited opportunities for engineer-to-order goods, e.g. ocean-going ships, because of their very large size and exacting performance requirements
DIY / DIWO	On-going opportunities for expansion of new DIY/DIWO companies that have pioneered VSP convergence Major opportunities in non-industrial developing countries because VSP convergence technologies reduce reliance on industrial skills and infrastructure for the manufacturing of goods	Technical challenges may be more formidable in non-industrial countries where Internet access and the supply of physical can be more haphazard

Conclusions

For practice

As summarized in Table 2, it has been explained how VSP convergence can address established barriers to the expansion of project manufacturing. For example, instead of time-consuming labour-intensive manual practices, unique data can be captured very quickly with digital cameras, digital videos, and/or digital scaners. Then, data can be converted very quickly with photogrammetry. Similarly, time-consuming labour-intensive manufacturing using general-purpose subtractive machinery can be replaced by digitally-driven additive manufacturing machines.

Table 2: VSP convergence to address limitations of traditional practice

Manufacturing phase	Examples of reduced barriers	
	Traditional practice	VSP opportunities
Data capture	Labour-intensive time-consuming manual 1D measurements	Digital cameras Digital scanners
Data conversion	Labour-intensive time-consuming manual formulation of 1D measurements into 3D representations	Photogrammetry
Design	Labour-intensive time-consuming CAD software requiring specialist professional expertise	Digital pens Intuitively understandable CAD Generative computation Social authoring of languages of design Blogs, forums, wikis enable sharing of design tips
Production	Labour-intensive time-consuming manual operation of subtractive general-purpose machinery, such as drills, lathes, and saws,	Languages of design linked to digitally-driven manufacturing equipment Digitally-driven manufacturing equipment Blogs, forums, wikis enable sharing of manufacturing tips
Assembly	Labour-intensive time-consuming assembly following drawings that use specialist terminology etc.	Physical scale models of full-size good Numbered snap fit joints Blogs, forums, wikis enable sharing of assembly tips

Moreover, VSP convergence can better enable project manufacturing businesses to either carry out work for customers or facilitate work by customers. Thus, project manufacturing can have potential to become a large-scale manufacturing paradigm alongside mass production and mass customization. This may be facilitated by the on-going improvement of technologies, and the introduction of a common categorization, such as mass imagineering, across different project manufacturing sectors.

For research

It can be argued that VSP convergence should bring about a shift of emphasis in manufacturing research. This is because the elimination of uncertainty from manufacturing of physical goods has hitherto been a priority since the beginning of the Industrial Revolution. Now, however, VSP convergence makes the elimination of uncertainty less of an imperative for improving manufacturing efficiency.

For example, in his book, An Inquiry into the Nature and Causes of the Wealth of Nations, Adam Smith advocated task specialization and speed through his famous parable of pin making. This specialization and speed was first made possible through the standardization of completed goods (i.e. mass production), then through the pre-design of components and the pre-determination of their potential configurations as completed goods (i.e. mass customization). Hence, a recent focus in manufacturing research has been increasing customer-specific variants of standard goods through mass customization.

Now, however, virtual-social-physical convergence can enable efficient manufacturing without having to pre-design goods or pre-design components and pre-determine their potential configurations. Thus, manufacturing can now also be advanced by increasing research into the project manufacturing of original goods that are based on the original ideas of individual customers.

References

Allen, J.P. (2010) Knowledge-sharing success in Web 2.0 communities, IEEE Technology and Society Magazine, 29(1), 58-64.

Anderson, C. (2013) *Makers: The New Industrial Revolution*, Crown Business, Random House Inc., New York, NY.

Anderson, C. (2012) Dreaming in 3D. Wired, October 1.

Baraniuk, C. (2013) Beyond 3D printing: The all-in-one factory. *New Scientist*, Issue 2930, 15th August.

Billinghurst, M. and Kato, H. (2002) Collaborative Augmented Reality. *Communications of the ACM*, 45(7), 64-70.

Bohlin, E., Brodin, K., Lundgren, A., and Thorngren, B. (2000) Convergence in Communications and Beyond, Amsterdam: Elsevier.

Brand, S. (1987) The Media Lab: Inventing the future at MIT, New York: Viking.

Brown, J.S. and Adler, R.P. (2008) Minds on Fire: Open Education, the Long Tail, and Learning 2.0. Educause Review, 43(1), 16–32.

Buckley, G., Henriques, M. and Salazar-Xirinachs, J.M. (2008) The Promotion of Sustainable Enterprises, International Labour Organization, International Labour Office, Geneva.

Buehen, A., Karmann, A. and Schneider, F. (2009) Shadow economy and do-it-yourself activities: the German case. Journal of Institutional and Theoretical Economics, 165(4), 701-22.

Dahl, T. (2012) 3-D design for idiots. Wired, June 13.

Dichter, T.W. (2003) Despite good intentions. University of Massachusetts Press, Amherst, MA.

Dwivedi, A., Merrilees, B., Sweeney, A. 2010. Brand extension feedback effects: A holistic framework. Journal of Brand Management, 17(5), 328-342.

Duysters, G., and Hagedoorn, J. (1998) Technological convergence in the IT industry: The role of strategic technology alliances and technological competencies. International Journal of the Economics of Business, (5)3, 355-368.

Farber, D.J. and Baran, P. (1977) The Convergence of Computing and Telecommunications Systems. Science, 195, 1166-1170.

Farquhar, P. H. 1989. Managing brand equity. Journal of Marketing Research, 26(1), 24-33.

Florida, Richard (2002) *The Rise of the Creative Class and How It's Transforming Work, Leisure and Everyday Life*, New York: Basic Books.

Fox, S. (2013) Paradigm shift: Do-It-Yourself (DIY) invention and production of physical goods for use or sale. *Journal of Manufacturing Technology Management*, 24(2), 218-234.

Fox, S. (2013) The new Do-It-Yourself (DIY) paradigm: financial and ethical rewards for businesses. Journal of Business Strategy, 33(1), 21-26.

Fox, S. (2011) A preliminary methodology for Generative Production Systems. Journal of Manufacturing Technology Management, 22(3), 348-364.

Fox, S. and Li, L. (2012) Expanding the scope of prosumption: a framework for analysing potential contributions from advances in materials technologies. Technology Forecasting and Social Change, 79(4), 721-733.

Fox, S., Jokinen, T., Lindfors, N., and Ylen, J.-P. (2009) Formulation of robust strategies for project manufacturing business. International Journal for Managing Projects in Business, 2(2), 217-237.

Gabor, A. and C. Granger, (1966) Price as an indicator of quality: report on an enquiry. *Economica*, 46, February, pp. 43-70.

Guth, R.A. (2007) How 3-D Printing Figures To Turn Web Worlds Real. The Wall Street Journal, December 12, p. B1.

Hansell, S. (2006) Yahoo's Growth Being Eroded by New Rivals. *The New York Times*, September 22.

Harmon, R.R., Unni, R.A. and Timothy, R. (2007) Price Sensitivity Measurement and New Product Pricing: A Cognitive Response Approach, in D.F. Kocaoglu, *Management of Converging Technologies.*

Hawk, D.L. and Artto, K.A. (1999) Factors impeding project management learning, Project Management, 5(1), 56-67.

Hayes, R. H. and S. C. Wheelwright. (1979) Link manufacturing process and product life cycles. *Harvard Business Review,* January-February, 133-140.

Howkins, John (2001) *The Creative Economy: How People Make Money From Ideas*, London: Penguin.

Kaplan, A.M. and Haenlein, M. (2010) Users of the world, unite! The challenges and opportunities of Social Media. *Business Horizons* 53(1): 59–68.

Kircher-Allen, E. (2009) Rwanda bids to become East Africa's WiFi hotspot. *Global Post*, December 30.

Knauth, O. (1949) Considerations in the Setting of Retail Prices. *Journal of Marketing*, 14 (July), 1-12.

Krish, S. (2011), A practical generative design method. Computer-Aided Design, 43(1), 88-100.

Kuzel A (1992) Sampling in qualitative inquiry. In: Crabtree B, Miller W (Eds) Doing Qualitative Research: *Research Methods for Primary Care* (Vol. 3). London: Sage, 31-44.

Li, G., Gao, F. and Wang, Z. (2011) A Photogrammetry-based System for 3D Surface Reconstruction of Prosthetics and Orthotics, 33rd Annual International Conference of the IEEE EMBS Boston, Massachusetts USA, August 30 - September 31.

Luhmann, T. (2010) Close range photogrammetry for industrial applications", ISPRS Journal of Photogrammetry and Remote Sensing, 65(5), 558–569.

Martin, J. (1978) The Wired Society: A Challenge for Tomorrow, Englewood Cliffs, NJ: Prentice-Hall.

McConnell, D. (1968) An experimental examination of the price-quality relationship. *Journal of Business*, October, 439-444.

McKeough, T. (2011) Got a Good Idea? Ben Kaufman of Quirky.com Will Be the Judge of That. *The New York Times*, August 24.

Milgram, P., and Kishino, A. F. (1994). Taxonomy of mixed reality visual displays, IEICE Transactions on Information and Systems, E77-D(12), 1321-1329.

Mone, G. (2010) Hacking the 21st-Century Auto. Popular Science, May 10.

Moyo, D (2009) Dead Aid: Why Aid Is Not Working and How There is Another Way for Africa. New York: Farrar, Straus and Giroux.

Nagle, T. and Holden, R. (2002) The Strategy and Tactics of Pricing. Prentice Hall.

Norton, K. (2006) Savile Row Never Goes Out of Style. BusinessWeek, October 31.

Ordanini, A., Miceli, L., Pizzetti, M. and Parasuraman, A. (2011) Crowd-funding: transforming customers into investors through innovative service platforms, *Journal of Service Management*, 22(4), 443 – 470.

Parks, R. (2012) Creation engine. Wired, October 1.

Powney, J. and Watts, M. (1987) Interviewing in Education Research, Routledge & Kegan Paul, London.

Patton M (2002) *Qualitative Evaluation and Research Methods*. London: Sage.

Prencipe, A. and Tell, F. (2001) Inter-project learning: processes and outcomes of knowledge codification in project-based firms, *Research Policy*, 30(9), 1373-94.

Rao, A.R. and Monroe, K.B. (1989) The Effect of Price, Brand Name, and Store Name on Buyers Perceptions of Product Quality: An Integrative Review. *Journal of Marketing Research*, 26(August), 351-357.

Rheingold, H. (2002) Smart Mobs: the next social revolution, Cambridge, Massachusetts: Perseus.

Rogers, E.M. (1962). *Diffusion of Innovations*, Glencoe: Free Press.

Robins, J. (2010) Standing the way: sustainable future vs. sloth, genes, and entrophy. IEEE Technology and Society Magazine, 29(3), 14-21.

Rusli, E. (2012) Facebook Buys Instagram for $1 Billion. *The New York Times*, April 9.

Sass, L. (2007) Synthesis of design production with integrated digital fabrication. *Automation in Construction*, 16(3), 298-310.

Smith, A. (2008) High-Speed Internet Coming to Africa. Time Magazine, September 15th.

Song, H., Guimbretiere, F. and Lipson, H. (2009) Capturing freehand annotations and edits to facilitate the 3D model design process using a digital pen. ACM Transactions of Computer-Human Interaction, 16(3), 14-33.

Stava, O., Vanek, J., Benes, B., Carr, N., and Mech, R. (2012) Stress Relief: Improving Structural Strength of 3-D Printable Objects. Purdue University.

Steers, R. M. and Porter, L. W. (1991) *Motivation and Work Behavior*, 5th edition, New York: McGraw-Hill.

Sterling, B. (2011) Arduino 1.0 arrives. Wired, December 1.

Stoetzel, J. (1970) Psychological/sociological aspects of price, in B. Taylor and G. Wills (eds), *Pricing Strategy*, , Princeton, NJ: Brandon Systems, 70-74.

The Economist (2011) Rebalancing the economy: Less paper, more iron: politicians want to boost British manufacturing. Easier said than done. The Economist, July 7.

Time Magazine (1942) The Place They Do Imagineering. February 16, p. 59.

Van Westendorp, P.H. (1976) *NSS-price sensitivity meter (PSM): a new approach to study consumer perception of prices*. Adformatie, Nederlandse Stichting Voor Statistiek (NSS): The Hague, 140-167.

Vance, A. (2012) How About Them Gams: 3D Printing Custom Legs. Bloomberg Businessweek, May 03

Von Tunzelmann, G.N. (1995) Technological accumulation and corporate change in the electronics industry. Mimeo, HCM Workshop, Urbino, February.

Vonderembse, M.A. amd White, G.P. (2007) *Operations Management: Concepts, Methods, and Strategies*, John Wiley & Sons, Chicester.

Williams, C.C. (2004) A lifestyle choice? Evaluating the motives of do-it-yourself (DIY) consumers. International Journal of Retail and Distribution Management, 32(5), 270-278.

Wright, A (2005) The Imagineering Field Guide to Magic Kingdom at Walt Disney World. New York: Disney Editions

PUBLICATION
II

The importance of information and communication design for manual skills instruction with augmented reality

Stephen Fox

Journal of Manufacturing Technology Management, 21(2), 188-205
https://doi.org/10.1108/17410381011014369

Fox, S. (2010) The importance of information and communication design for manual skills instruction with augmented reality. Journal of Manufacturing Technology Management, 21(2), 188-205.

Abstract

Purpose - There are guidelines for information and communication technology (ICT) applications which are already established in manufacturing. These guidelines include recommendations such as: alignment of ICT applications with strategy; involvement of the full range of stakeholders; careful planning and monitoring. A recommendation from outside of manufacturing is that information and communication design should be carried out in conjunction with ICT applications. The purpose of the research reported in this paper was to investigate the relevance of information and communication design to applications of advanced ICTs used in the instruction of manual skills

Design / methodology / approach - Literature review, interviews, and five quasi-experimental studies.

Findings - The design of information and its communication is relevant to the instruction of manual skills with ICTs and, in particular, important for instruction with augmented reality.

Research limitations - There were only ninety-two participants in the five quasi-experimental studies.

Practical implications - This paper provides an overview of information and communication design issues. Examples are provided of how these issues manifest themselves in the application of advanced ICTs, such as virtual reality and augmented reality, which can be used in the instruction of manual skills.

Originality / value - The originality of the research reported in this paper is that it goes beyond further investigation of established guidelines for ICT applications. The value of this paper is that it draws attention to the potential of information and communication design to improve ICTs implementations. It also draws attention to the need for balanced comparisons in the assessment of all ICTs prior to their implementation.

Keywords: information and communication technology; information and communication design; technology management.

Paper type: research paper

Introduction

Applications of information and communication technologies have potential to improve the performance of manufacturing (Jiang and Fukuda, 2007; Ketikidis, Koh and Gunasekaran, 2006; Srinivasan and Jayaraman, 1999; Zerenler, 2007). However, it has long been recognized that applications of information and communication technologies can be unsuccessful (Maskell, 1993; Melnyk and Narasimhan, 1992; Prouty, 2000; Monnoyer, 2003). Accordingly, guidelines for information and communication technologies (ICT) applications have been proposed. Such guidelines can be specific to manufacturing (e.g. Ake, Clemons, Cubine and Lilly, 2004) or relevant to ICT applications in any sector (e.g. OECD, 2003). Typically, guidelines include recommendations such as: alignment of ICT applications with strategy; involvement of the full range of stakeholders; careful planning and monitoring (Dedrick, Gurbaxani and Kraemer, 2003; Ross and Weill, 2002).

A less widely recognized recommendation from outside of manufacturing is that the formulation and communication of information with ICTs should be designed. Information design seeks to improve the effectiveness of information for specific audiences / recipients (Jacobson, 1999). Communication design is concerned with the selection of media most suitable for carrying particular information to specific audiences / recipients (Barry and Fulmer, 2004). It has been argued that the design of information and its communication can bring about improvements in the performance of individuals (Schwartz and Hartman, 2006) and organizations (Devlin and Rosenberg, 1996). The design of information and its communication may be relevant to instruction of manual skills with ICTs such as virtual reality and augmented reality.

Shortages of manual skills are reported by manufacturers throughout the world (Katz, 2008). Currently, manual skills are often communicated through one-to-one interaction between a person with manual skills (e.g. an instructor) and a person lacking manual skills (e.g. a trainee). As there is shortage of people with manual skills, so there is a shortage of people who are available to provide instruction in manual skills. Moreover, one human instructor can only be in one place at one time; and only a few trainees can be at that place to receive instruction at one time. By contrast, advances in ICT may make it possible to reduce dependency on human instructors by enabling individual trainees to receive personal instruction in-situ where ever they are.

The research reported in this paper explored relevance of information and communication design to the use of ICTs for instruction of manual skills. The research included literature review, interviews, and five quasi-experiment studies. The research included field work in the following countries: Finland, Italy, Japan, South Korea. The research was carried out throughout 2007 and 2008. The remainder of this paper is organized into five major sections. In the next section, future need for manual skills is considered. In the third and fourth sections, information and communication design is described in more detail. In the fifth section, the relevance of information and communication design to instruction of manual skills with ICTs is examined. In the final section, the conclusions of the research are outlined, together with directions for future research.

Future need for manufacturing skills

Manual skills can be classified in terms of fine and/or gross psychomotor functioning (Gilchrist and Gruber, 1984). Manual skills involve psychomotor functioning in the manipulation of handheld tools and the positioning of components. Fine motor functioning involves neuromuscular coordinations that are usually precision orientated and involve hand-eye coordination. Gross motor functioning involves use of the large muscles of the body; often with the whole body being in movement.

Manual skills can also be classified in terms of how much initiative people are able to draw upon when undertaking tasks in different situations. In particular, people can be routine experts or they can be adaptive experts (Lin, Schwartz and Bransford, 2007). Adaptive experts are able to discern the specific, and often subtle, features that differentiate one situation from another. Further, they have the ability to modify or invent skills according to the requirements of that situation. Moreover, adaptive experts avoid the unproductive application of previously useful prior learning in new situations. This can be very important because the nature of the situation determines the nature of the successful pattern of movement for a particular motor skill (Gentile, 1977). In other words, adaptive experts are able to draw upon initiative to deal with a wide variety of different situations. However, there are many situations where adaptive expertise is not needed, and routine expertise is sufficient. For example, typing is a skill with extremely stable manual skill requirements. Accordingly, the instruction of such manual skills should aim to make sure that people develop good initial habits, so they can become increasingly efficient without ever having to undo their prior learning (Schwartz, Lindgren and Lewis, 2009).

Investigation of requirements for manual skills included visits to seventeen companies in the following countries: Finland (1), Italy (3), Japan (6), and South Korea (7). The companies were selected because labour costs are relatively high in the countries in which they operate, and they face intense international competition. Accordingly, these companies have progressed through on-ongoing commitment to implementing technological advances. It was considered that such companies were less likely to persist with manual skills than companies which operate in countries with lower labour costs and which do not face intense international competition. The outputs of the companies' activities can be ordered in terms of physical size as follows: ships; cars; fork lift trucks; factory automation equipment; machine tools; hoists; moulds for automotive and consumer electronics components;

automotive components; home electronics; desk-top manufacturing equipment; actuators and values; mobile telephones. Company production managers were asked: what manual skills, if any, will your company need in the future? All of the companies visited envisaged that they would continue to need manual skills in their operations. However, not all of the companies had requirements for both fine and gross motor skills; or for adaptive expertise as well as routine expertise.

Car makers (Italy; Japan; South Korea) foresaw a reduction in the pool of potential operatives available for recruitment. Accordingly, they seek to reduce the physical demands of assembly tasks that will continue to be carried out by human operatives. For example, by developing improved intelligent assist devices for use by human operatives in the positioning of windscreens. Accordingly, it is possible that gross psychomotor skills will not be required in the future. However, the initiative of adaptive expertise is likely to continue to be important to car makers that need their operatives to evaluate outputs and plan means of improvement during Kaizen (Imai, 1986).

With regard to the assembly of mobile phones (South Korea), a production manager stated that automation becomes a bottleneck when the variety of mobile phone models in production increases. Accordingly, the company had reverted back to the use of human operatives and jigs in its assembly operations because the number of different products it assembled per day had increased. Companies making home electronics, desk-top manufacturing equipment, actuators and values, were all found to be making extensive use of human manual skills (Japan). Fine motor skills are particularly important in these companies.

These findings are consistent with literature that draws attention to the importance of workforce and skills (Bennour and Crestani, 2007; Fraser, Harris and Luong, 2007; Gaimon, 2008). These findings are also consistent with past cases of companies and industries that found it necessary to cut back on automation and re-introduce human operatives in order to develop quality, improve productivity and increase profitability (Agrawal and Kumaresh, 2001; Davenport and Prusak, 2000; The Economist, 1995).

In the next two sections, information and communication design issues, which have potential to inform applications of ICTs for manual skill instruction, are described. These issues were revealed through interviews with experts in semantics (10); translation (10); information and communication design (10); and use of ICTs for instruction (10). The informant style of unstructured interview was used (Powney and Watts, 1987). The interviewer did not seek to control the interviews. Rather, interviewees freely expressed their thoughts and took the interviews in the direction that they chose. This type of unstructured interview can be contrasted to the respondent style of unstructured interview where the interviewer seeks to follow a more defined agenda (Powney and Watts, 1987). Notes were hand written by the interviewer. Unstructured interviews were followed up with literature reviews. The literature reviews followed topics which interviewees stated to be important in their opinions.

Information and communication design - underlying issues

Information design

Information design seeks to improve the effectiveness of information. Underlying issues in information design can be categorized as conceptual, presentational, and linguistic. Conceptual issues can span across disciplines and nationalities. For example, studies suggest that the spatio-temporal mental models formed by native speakers of the Ural-Altaic family of languages, such as Finnish, differ from those formed by native speakers of Indo-European languages, such as English (Stromnes, 1974). This difference manifests itself in the relatively limited use of future tense by native Finnish speakers when compared to native speakers of English. Conceptual differences between nationalities are common (Wierzbicka, 1992). For example, there is no direct equivalent of the concept, fair, in Japanese culture (Kidder & Miller, 1991). Conceptual ambiguities within individual nationalities are also common. For example, the Finnish word, nettohyöty, (net benefit) may refer to either benefits minus cost or to benefits compared to a base line situation. Thus, one term refers to two related but different concepts. Moreover, there can be challenges when seeking to define new technological concepts and business concepts. Particularly, when the emerging technical jargon and buzzwords associated with them are very open to interpretation.

Presentational issues include color, sound and layout (Roberson, Davidoff, Davies & Shapiro, 2004). People's perception of colour can depend upon their cultures. For example, death may be symbolized by black in some cultures and white in other cultures; red is auspicious in China but associated with warning in the USA. More generally, bright colours many be viewed less favorably by Asians than Europeans (Simon, 2001). On the other hand, Asians may regards sound effects more favorably (Evers, 2001). Further, the layout of communications can be perceived differently among different nationalities (Marcus & Gould, 2000). It has been argued that indirect and cyclical layouts, such as navigational schema, may be regarded more favorably among nationalities that have indirect and cyclical approaches to their conversations and writing styles (Wurtz, 2005).

Linguistic issues can be described as lexical, syntactic, semantic and phonological. Lexical ambiguity (Duffy, Morris & Rayner, 1988; Simpson, 1981) can arise when a word, has more than one meaning. Lexical ambiguities can arise from homonyms, heteronyms and Capitonyms. Examples include: sanction (to punish or to approve); desert (to abandon or arid region); polish (to shine), Polish (from Poland). Syntactic ambiguities (Ferreira & Henderson, 1990; Snedeker & Trueswell, 2004) can arise from sentences that can be parsed in more than one way. Parsing may involve different readers / listeners breaking up sentences into different chunks and attributing different means to those different chunks and therefore the whole sentence. Semantic ambiguity can arise when the meaning of a sentence could be determined only with the help of greater knowledge sources (Baker, Franz, & Jordan, 2001). This is likely when idiomatic phrases are used (Small, Yelland, Lumley, Rice, Contronei, & Warren, 1999). Also, semantic ambiguity can arise if the same words elicit different cognitive or emotional states (Schaffer & Riordan, 2003). Phonological ambiguity can arise when a set of sounds can be interpreted in more than one way (Frost, Feldman, & Katz, 1990). A summary of issues underlying information design is provided in Table 1. This table also provides a summary of the communication design issues which are considered in the following paragraphs.

Table 1: Underlying issues in information and communication design

Field of design	Underlying issues	Example
Information	Conceptual	Spatio-temporal mental models
	Presentational	Perceptions of colour, sound, layout
	Linguistic	Lexical; syntactic; semantic; phonological
Communication	Technical	Transmission velocity; parallelism; symbol variety
	Ergonomic	Affordances; constraints
	Social	Experiences; norms; knowledge of sender

Communication design

Communication design is concerned with the selection of media most suitable for carrying particular information to specific audiences / recipients. The underlying issue in communication design can be categorized as technical, ergonomic, and social. Technical capabilities of media have been defined (Dennis, Fuller & Valacich, 2008) as transmission velocity (i.e. the speed at which a medium can deliver a message to intended recipients); parallelism (i.e. the number of simultaneous conversations that can exist effectively); symbol variety (i.e. the number of ways in which information can be communicated); rehearsability (i.e. the extent to which a medium enables the sender to rehearse or fine tune a message before sending); and reprocessability (i.e. the extent to which a message can be re-examined or processed again).

Ergonomic characteristics of media can afford or constrain different types of usage. Paper, for example, affords some types of usage that a computer monitor, for example, constrains. In particular, paper is spatially flexible. In other words, it can be spread out across tables for many people to gather around at the same time. Further, paper can be placed up close to physical artifacts. For example, when the condition of a leased vehicle needs to be checked against a visual diagram in order for any damage to be recorded. Further, annotations can be written onto paper without altering the original content. On the other hand, a computer monitor can afford opportunities (i.e. affordances) to view many different types of information simultaneously (Gladwell, 2002). In comparison, information on one piece of paper is more fixed. In order to combine the affordances of physical media and digital media, and at the same time to reduce their respective constraints, paper-based interfaces have been combined with personal computer-based systems (Liao et al, 2007). Further, cordless digital pens are being introduced that can be use write on any paper but record onto a computer at the same time (Pogue, 2008). The writing made on paper appears on the writer's computer as a digital image which can be converted into text. This means that people do not have to carry a laptop with them to in order to get notes onto their computer. Further, the text can be communicated to many other people in distributed locations via email, for example, at the same time as a few people in the same location look at the written work on paper.

In addition to technical and ergonomic issues, the utility of communication media can be partially socially defined (Fulk, Steinfield, Schmitz & Power, 1987; Schmitz & Fulk, 1991). This means that experiences and norms, as well as knowledge of the sender (Sproull & Kiesler, 1986) can alter perceptions of a medium's information-carrying capacity, and these perceptions may change over time (McGrath, 1993; Jaffe, 2000). Perceptions can be influenced by culture (Straub, 1994), gender (Gefen and Straub, 1997) and personality type (Byron and Baldridge, 2007; Peter and Valkenburg, 2006). Moreover, it is possible for one medium to possess different levels of information-carrying capacity depending upon how it is configured and used. For example, one electronic mail system may have a limited symbol variety (text only) while another has a much wider symbol variety (text, graphics and video). The term symbol variety refers to the number of ways in which information can be communicated. However, it should not be assumed that more symbol variety always equals better symbol variety. For example, within face-to-face communication there is evidence that non-verbal communication can be more effective than verbal communication (Dickey, 1991; Hollingsworth, 1973). In particular, there is evidence that face-to-face communication comprising only gestures can be more effective in some situations than face-to-face communication comprising speech and gestures (Lozano & Tversky, 2006).

Overall, a variety of technical capabilities, ergonomic characteristics, and social associations can be attributed to different media: each of which may be more or less important for a particular task (Brennan and Lockridge, 2006). Hence, it is argued that no one medium can be labelled as having the best information-carrying capacity (Dennis, Valacich, Speier and Morris, 1998), and that ranking media in absolute terms is not practical. Moreover, choosing one single medium for any task may prove less effective than choosing a variety of media which a team uses at different times to perform different tasks (Chidambaram and Jones, 1993; Olaniran, 1994; Rubens, 2003).

Information and communication design - application issues

Analysis, demonstration, and feedback

Instruction of psychomotor skills without human instructors is challenging because psychomotor skills involve tacit, procedural knowledge that is difficult to verbalize. Accordingly, careful analysis of psychomotor skills should be carried out to inform development of training information for their instruction (Jonassen, Hannum and Tessmer, 1989). For example, information should direct trainees' attention to those details of skill execution which have most influence on success; such as the positioning of hand grip on a tool; the extent of joint movement; etc. Due to the limitations of verbal and/or written explanations of such knowledge, psychomotor skills are often instructed through repeated physical demonstrations by a human instructor.

Further, human instructors provide feedback about practice. This is essential to the development of proficiency in manual skills (Magill, 2004; Schmidt and Lee, 2005). Knowledge of results is terminal feedback provided to the learner after the completion of the task relative to the goal of the task. Knowledge of performance refers to the pattern of motion produced when performing a manual skill task. Knowledge of results can be provided in two ways: intrinsic or extrinsic. Intrinsic knowledge of results is available when tasks that have knowledge of results "built in to them". For example, if a nail is bent over when the task is to knock a nail straight into a piece of wood. By contrast, extrinsic knowledge of results and/or performance is evaluation information provided after the completion of a task from some source outside the task. It has been argued that without extrinsic feedback, learners will learn only to be consistently wrong - without realizing that they are wrong (Kaufman, Wiegand and Tunick, 1987). The timing, frequency and content of feedback can all have a determining effect on the success and speed of learning (Chiviacowsky and Wulf, 2007).

Fostering adaptive expertise

The type of instruction required to foster the initiative of an adaptive expert is different to the type of instruction required for the development of routine expertise. The type of instruction required for the development of routine expertise can be described as "Tell-and-Practice". This means that learners are given a formulaic solution for a type of problem. Then, they practice applying the solution which they have been given. In instructional terms, a problem can be described a gap or barrier between a goal state and a present state (Hayes, 1989). The limitation of "Tell-and-Practice" methods is that learners focus on the formulaic solution, rather than the generalizable structure of the problem situations. Hence, they are left with memories for the formula and the obvious surface features of problems (Schwartz and Bransford, 1998).

The type of instruction required to foster adaptive expertise can be described as Invent-Tell-and-Practice. In this type of instruction, trainees are first asked to "Invent" their own explanations for instances of a type of problem (Schwartz and Martin, 2004). The instances that they are given are similar, but vary on one or two dimensions. These somewhat different instances of a problem type can be described as contrasting cases. The juxtaposing and analysing of contrasting cases prepares learners to understand deeply the generalizable structures of problems and the subsequent solutions that they receive during the "Tell" part of their instruction. This is because learners are interested to be told the significance of the distinctions that they have discovered and the principles that explain these distinctions. Further, the retention of instruction can improve because people tend to remember better those things that are meaningful to them (Leavitt and Schlosberg, 1944). Thus, learners can become adaptive experts. That is people who have sufficient initiative: to discern the features that differentiate one situation from another; to understand the significance of those features; to modify or invent skills according to the requirements of that situation; and to avoid the unproductive application of previously useful prior learning in new situations.

It is important to note that a person with adaptive expertise can also make good use of routine expertise. This because many challenging problems include sub-problems that can be solved using prior learning that has been useful many times in the past. Such applications of routine expertise free up "attentional bandwidth", and enable concentration on other aspects of a new situation that may require non-routine adaptation (Schwartz, Bransford and Sears, 2005).

Assessment of relevance

Assessing the relevance of information and communication design to instruction of manual skills with ICTs was facilitated by five sequential studies. All of the studies involved two groups of participants. In all of the studies, one group of the two groups used Augmented Reality (AR) instructions. Augmented Reality (AR) can enhance users' perceptions of the real world by showing additional information such as graphics and/or text. This additional information can be viewed in-situ, at the same time as the real world, via a variety of media including computer monitor, laptop screen, mobile telephone screen, and head mounted display. It has been argued that AR is one of the technologies most likely to alter industries (Jonietz, 2007). Further, it has been claimed that AR has the potential to enable instruction without human instructors (Boud, Haniff, Baber, and Steiner, 1999; Pathomaree and Charoenseang, 2005). In all of the studies, the other of the two groups used instructions comprising Virtual Reality (VR) graphics. Both types of instructions provide information about how to assemble the same wooden puzzle comprising the same six wooden pieces (Figure 1a) and square wooden box (Figure 1b). The AR instructions are shown in Figure 1c, and the VR instructions are shown in Figure 1d.

Assembly involves putting each wooden piece in its correct position and sequence in a square wooden box with an open top. In all of the studies, each participant selected and positioned the physical wooden pieces when following the AR or VR instructions. Each participant worked individually and took part in only one study. Details of the studies are summarized in Table 2.

Figure 1 Pieces and Instructions

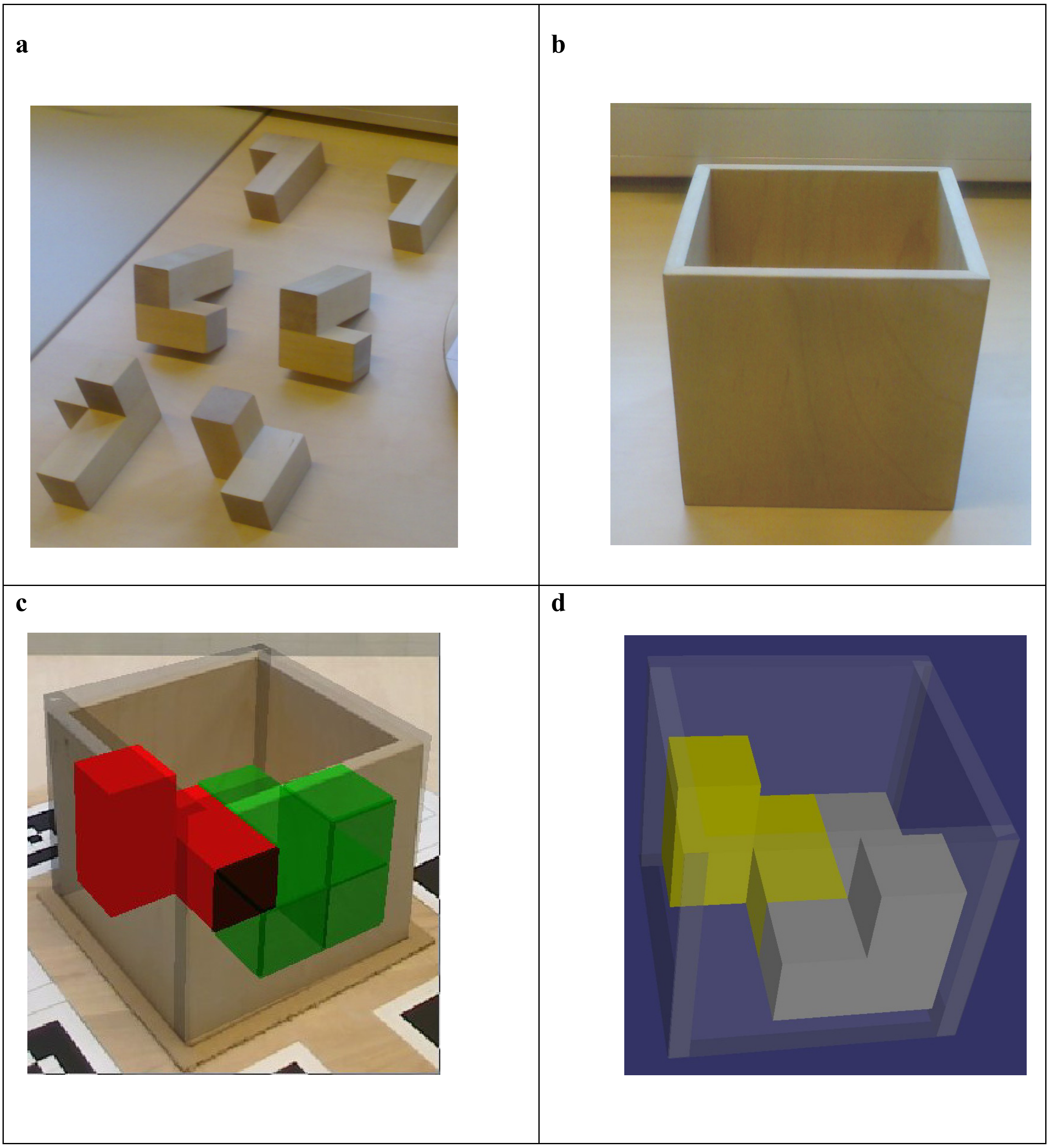


Table 2 Study Details

Details		Study Number 1	2	3	4	5
No. of Participants		12	20	20	20	20
Media	AR	Monitor	Monitor	Monitor	Laptop	Laptop
	VR	Paper	Paper	Paper	Laptop	Laptop

Fox, S. (2010) The importance of information and communication design for manual skills instruction with augmented reality. Journal of Manufacturing Technology Management, 21(2), 188-205.

Each group comprised an equal number of female and male participants. The participants were not a random sample. Rather, a purposive sample of professional people whose work involves the use of advanced ICTs was obtained. In the first three studies, the AR instructions were viewed via a 19 inch computer monitor, while the VR instructions were printed out and viewed via six separate pieces of paper which were held in a lever arch file. In the final two studies, both AR instructions and VR instructions were viewed via a 14 inch laptop screen. The studies were not fully defined at the outset. Rather, studies evolved based on observations of the preceeding studies. Observations enabled deeper analyses of the assembly task, and of the information and communication design for the application of the ICTs. These analyses prompted revision of instructions for each following study. Further information about each of the studies is provided in next five sub-sections.

Study One

In the first study, participants were asked to follow the instructions, but they were not asked to subsequently assemble the puzzle without instructions. All of the attempts to assemble the puzzle were successful. Following the AR instructions via the computer monitor took, on average, more than three times longer than following the VR graphics instructions on paper. In this first study, as in the second and third studies, the six steps in the AR instructions were moved forward or backwards by pressing the arrow keys on a conventional keyboard. Participants were observed to be very methodical in their use of the AR instructions. By contrast, participants appeared to turn the pages of the VR graphics as quickly as possible.

Study Two

In the second study, participants were asked to follow the instructions. At the same time, they were told that they would subsequently assemble the same puzzle without instructions. They were also told that the purpose of following the instructions was to learn how to assemble the puzzle without instructions. Participants assembled the puzzle without instructions immediately after having completed the assembly once by following the instructions. Interestingly, the time taken to follow the VR instruction was much longer than in Study 1, because participants turned the pages much more slowly after looking much more carefully at the graphics. In this study, 80 percent of the people following the VR instructions were subsequently able to assemble the puzzle. By contrast, only 30 percent of people following the AR instructions were subsequently able to assemble the puzzle. Further, the average time taken for subsequent assembly by participants who had followed AR instructions was more than three times longer than the average time taken by participants who had followed VR instructions. One participant remarked: "the AR instructions were OK for identifying the piece but not for seeing where to put the pieces in the box".

Study Three

It was observed that most of the assembly difficulties in Study 2 involved the positioning of the first two pieces. In Study 3, all participants were asked to pay particular attention to the shapes and position of the first two pieces. This was the only difference in the instructions between Studies 2 and 3. As shown in Table 3, the time taken to follow both AR and VR instructions decreased by about a quarter. Also, the time taken to subsequently assemble after following AR instructions was more than halved. Further, the percentage of successful completions was 90 for both groups. Interestingly, one of the participants who failed to complete the assembly remarked: "the AR is too exciting to remember".

Table 3 Study Results

Measure		Study Number 1	2	3	4	5
Time take to follow instructions (seconds)	AR	142	161	128	144	218
	VR	46	129	99	96	102
Time take to complete assembly (seconds)	after AR	N/A	245	117	61	76
	after VR	N/A	66	65	56	68
Successful completions (percentage)	after AR	N/A	30	90	80	80
	after VR	N/A	80	90	90	80

Study Four

The instructions for Study 4 were the same as for Study 3, other than both AR instructions and VR instructions were viewed via a 14 inch laptop. The VR instructions were presented in the form of a presentation comprising six slides. Participants were able move from one slide to another by pressing the arrow keys on the laptop. The AR instructions were also moved forward or backwards using the arrow keys on the laptop. Thus, both groups now viewed and operated their respective instructions in the same way. It was in this study that the average time taken to follow AR instructions was closest to the average time taken to follow VR graphics instructions. Also, there was little difference between the two group's percentages of successful completions. One participant remarked that: "the inclination of the laptop screen is important to getting a good visualization".

Study Five

It was observed that the most of the assembly difficulties in Studies 3 and 4 arose from participants being uncertain as to the orientation of the first wooden piece on its Y axis. If the first piece is not orientated correctly, the second piece cannot be positioned correctly. In an effort to overcome this problem, the AR instructions were reprogrammed so that what had been the second piece was now instructed to be selected and positioned first. Similarly, the sequence of the VR graphics instructions was re-ordered. This attempt to correct an observed assembly problem created another assembly problem. In particular, participants were observed to have difficulties in positioning the new first piece. These difficulties were observed to be more challenging among the participants following the AR instructions. One of these participants remarked that: "it would be better if the edges of the shapes were in black line". Another participant following the AR instructions remarked: "the edges of the shapes were not clear enough". None of the participants in the previous four studies had made any remarks about the edges of the shapes. This may have been because the new first piece was not the full length of the square open box into which the puzzle pieces are placed. By contrast, all of the other pieces are the full length. All of the durations were longer in Study 5 than in Study 4.

Assessment of relevance

Not all of the underlying issues in information and communication design were relevant to the five studies. In particular, the studies comprised a simple assembly task that involved physical work pieces. Accordingly, conceptual issues underlying information design were not significant. Further, the studies involved little use of natural language. Accordingly, linguistic issues underlying information design were not significant. By contrast, presentational issues underlying information design were significant. For example, it was notable that participants criticised AR information for lack of edge definition in Study 5. This highlights that; although AR information may have the potential to be more easily understood by more people because it presents additional instructional information in the same view as the real world; AR information can overlay key information in the real world and, as a result, reduce clarity. Moreover, this overlaying of key information in the real world may only be counterproductive when information is configured in a particular way. In Studies 1 to 4, for example, the lack of edge definition was not criticised.

With regard to communication design, ergonomic characteristics were an important issue. For example, paper afforded participants the opportunity to place instructions much closer to the physical pieces to be assembled than instructions viewed via computer monitor. Also, changing the communication of AR instructions from a monitor to a laptop was followed by the time taken to assemble being reduced by almost half. This may have been because participants could look at both the physical pieces and the AR information without changing the inclination of their views. The technical capability of transmission velocity was also an issue: with the medium of paper being able to deliver information to participants more quickly than either computer monitor or laptop screen. Further, it is possible that the utility of AR could have come to be socially defined after the studies had been completed. This is because the participants who used AR offered many more criticisms than participants who used VR graphics.

Not all of the application issues of information and communication design were relevant to the five studies. In particular, the studies did not encompass extrinsic feedback - only the intrinsic feedback of the puzzle pieces either fitting or not fitting together. With regard to analysis, adding the instructional information, "pay particular attention to the first two pieces", was followed by a notable reduction in times and a notable increase in the number of successful completions. Conversely, the re-ordering of the first two pieces was followed by a notable increase in the time taken to follow AR instructions. This outcome highlights that analysis should identify those details of execution which have most influence on failure, as well as success.

With regard to the fostering of adaptive expertise, it is notable that, while all participants were able to complete the task successfully when following the instructions, not all of the participants were able to subsequently complete the task successfully without instructions. This happened even though participants assembled the puzzle without instructions immediately after having completed the assembly by following the instructions. As discussed above, Tell-and-Practice yields inferior learning compared to Invent-Tell-and-Practice. Yet, AR instructions offer the prospect of Tell only instruction; with the possible consequence of no learning whatsoever. This is because the presentation of factual information is not nearly enough to enable learning (Bransford, Jeffery, Franks, Vye and Sherwood, 1989; Gragg, 1940). Accordingly, manufacturing companies which are enthralled by the potential of AR to communicate product assembly instructions in real-time at their factories should consider the potential disbenefits that could arise if no skill learning is enabled. In particular, the failure to develop and harness human expertise can lead to companies becoming uncompetitive (Davenport and Prusak, 2000).

Conclusions

Literature and field study indicate that manual skills will continue to be essential to the manufacture of a wide range of physical goods, including: ships; cars; fork lift trucks; factory automation equipment; machine tools; hoists; home electronics; actuators and values. The tentative conclusion of the research reported in this paper is that the design of information and its communication is relevant to instruction of manual skills with ICTs. Not all of the underlying issues and application issues were relevant to the studies that were carried out during the research. However, those that were relevant; presentational issues, ergonomic characteristics, technical capabilities, and analysis; did influence results.

A further tentative conclusion is that information and communication design is particularly important for skill instruction using augmented reality (AR). This is because, for example, AR information can have the unintended consequence of reducing clarity by overlaying key information in the real world. Further, AR information can be communicated at point-of-use in real-time, and hence offers the seemingly attractive prospect of on-demand manual skill instruction which transcends traditional requirements for training. However, such an approach could eventually lead to workforces which lack adaptive expertise. Overall, it could be argued that augmented reality may not prove to be a superior ICT for the instruction of manual skills - unless particular attention is paid to information and communication design. Interestingly, the importance of information and communication design has not been considered in previous AR studies by others. However, examination of other studies may reveal that the investment made in AR far exceeded the investment in the alternative against which AR was assessed. Moreover, this imbalance led to the alternative having extremely limited potential to communicate information. In one study of skill transfer in assembly task, for example, some groups followed AR instructions, while other groups watched manual assembly by another person. Hence, the non-AR groups did not practice selection and positioning of pieces. Further, the pieces assembled were small and, therefore, partial covered by the hands of the person who demonstrated the assembly to the non-AR groups. By contrast, in this research an equal investment was made in the AR instructions and the VR graphics against which they were compared. Thus, the research highlights that balanced comparisons are essential to answering a long-standing question about the bold claims which are sometimes made for new ICTs. That question is: what's spurious and what's real (Hempell, 2002).

One philosophy for guiding more balanced future research into the potential consequences of investments in ICT is critical realism (Mingers, 2004). This philosophy of science has been developed as an alternative to positivism and interpretivism. The purpose of critical realism is to improve understanding of causal mechanisms and contexts that are needed in order to achieve outcomes from actions (Carlsson, 2003). Mechanisms for the instruction of manual skills are demonstration, practice and feedback. The contexts are training centers and on-the-job. Future research can explore the potential of different ICTs to reduce the dependency of mechanisms on human instructors. Research can encompass the details of information and communication design, such as when the edges of graphics should, and should not, be emphasized in black line. Moreover, research can encompass the overall scope of information and communication design. For example, the communication of information describing contrasting cases is not necessary if the development of adaptive expertise is not required. Most importantly, research should be balanced by exploring potential disbenefits, as well as potential benefits. This need for balanced research is relevant to all ICT applications, not only those with potential to enable instruction of manual skills.

Fox, S. (2010) The importance of information and communication design for manual skills instruction with augmented reality. Journal of Manufacturing Technology Management, 21(2), 188-205.

References

Agrawal, M., Kumaresh, T.V. and Mercer. G.A. (2001) The False Promise of Mass Customization. *McKinsey Quarterly*, 3.

Ake, K., Clemons, J., Cubine, M. and Lilly, B. (2004) *Information technology for manufacturing: reducing costs and expanding capabilities*. CRC Press, Boca Raton, FL.

Baker, K.L., Franz, A.M., and Jordan, P.W. (2001) *Coping with Ambiguity in Knowledge-based Natural Language Analysis*, Center for Machine Translation and Department of Philosophy, Carnegie Mellon University.

Barry, B. and Fulmer, I.S. (2004) The medium and the message: the adaptive use of communication media in dyadic influence. *Acadamy of Management Review*, 29: 272-292.

Bennour, M. and Crestani, D. (2007) Formalization of a process activity performance estimation approach using human competencies. *International Journal of Production Research*, 45(24), 5743-5768.

Boud, A.C., Haniff, D.J., Baber, C. and Steiner, S.J. (1999) Virtual reality and augmented reality as a training tool for assembly tasks. In *Proceedings of 1999 IEEE International Conference on Information Visualization*, pp. 32-36.

Bransford, J.D., Franks, J.J. Vye, N.J. and Sherwood, R.D. (1989) New Approaches to Instruction: Because Wisdom Can't Be Told. In *Similarity and Analogical Reasoning,* S. Vosniadou, Andrew Ortony (eds). Cambridge University Press, New York.

Brennan, S.E. and Lockridge, C.B. (2006) Computer-mediated communication: a cognitive science approach. In K. Brown (Ed.), ELL2, *Encyclopedia of Language and Linguistics*, 2nd Edition (pp. 775-780). Oxford, UK: Elsevier Ltd.

Byron, K. and Baldridge, D.C. (2007). E-mail recipients' impressions of senders' likability. *Journal of Business Communications*, 44(2), 137-160.

Caple, C. (1996) *The effects of spaced practice and spaced review on recall and retention using computer assisted instructions*. Ann Arbor, MI: UMI.

Carlsson, S.A. (2003) Advancing information systems evaluation (research): a critical realist approach. *Electronic Journal of Information Systems Evaluation*, 6(2), 11-20.

Chidambaram, L. and Jones, B. (1993) Impact of communication medium and computer support on group perceptions and performance: a comparison of face-to-face and dispersed meetings. *MIS Quarterly*, 17(4), 465-491.

Chiviacowsky, S. and Wulf. G. (2007) Feedback after good trials enhances learning. *Research Quarterly for Exercise and Sport*, 78: 40–47.

Davenport, T.H. and Prusak, L. (2000) *Working Knowledge: how organizations manage what they know*. Harvard Business School Press, Boston.

Dedrick, J., Gurbaxani, V and Kraemer, K. (2003) Information Technology and Economic Performance: A Critical Review of Empirical Evidence. *ACM Computing Surveys*, 35, 1-28.

Dennis, A.R., Fuller, R.M. and Valacich, J.S. (2008) Media, tasks, and communication processes: a theory of media Synchronicity. *MIS Quarterly,* 32(3), 575-600.

Dennis, A.R., Valacich, J.S., Speier, C. and Morris, M.G. (1998) Beyond media richness: an empirical test of media synchronicity theory. *Proceedings of the 31st Hawaii International Conference of System Sciences*.

Devlin, K. (2001) *InfoSense: Turning Information into Knowledge*. New York, NY: W.H. Freeman and Company.

Evers, V. (2001) *Cultural aspects of user interface understanding: an empirical evaluation of an e-learning website by international user groups*. Open University, Milton Keynes, UK.

Dickey, M.R. (1991) A comparison of verbal instruction and nonverbal teacher student modeling in instrumental ensembles. *Journal of Research in Music Education*, 39: 132-142.

Duffy, S.A., Morris, R.K., and Rayner, K. (1988) Lexical ambiguity and fixation times in reading. *Journal of memory and language*, 27 (4), 429-446.

Ferreria, F., and Henderson, J.M. (1990) Use of verb phrasing in syntactic parsing: evidence from eye movements and word-by-word self-paced reading. *Journal of experimental psychology. Learning, memory, and cognition*, 16 (4), 555-568.

Fraser, K., Harris, H. and Luong, L. (2007) Team-based cellular manufacturing. *Journal of Manufacturing Technology Management*, 18(6), 714-730.

Frost, R., Feldman, L.B., and Katz, L. (1990) Phonological ambiguity and Lexical ambiguity: Effects on visual and auditory word recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 16, 569-580.

Fulk, J., Steinfeld, C.W., Schmitz, J. and Power, J.G. (1987) A social information processing model of media use in organizations. *Communication Research*, 7(4), 529-552.

Gaimon, C. (2008). The management of technology: a production and operations management perspective. *Production and Operations Managment*, 17(1), 1-11.

Gefen, D. and Straub, D.W. (1997) Gender differences in the perception and use of e-mail: an extension to the technology acceptance model. *MIS Quarterly*, 21(4), 389-400.

Gentile, A.S. (1977) The effects of symoblic modeling and behavior rehearsal on assertive training with prison inmates. *Dissertation Abstracts International*, 38.

Gilchrist, J.R., Gruber, J.J. (1984). Psychomotor domains. *Motor Skills: Theory into Practice*, 7: 57-70.

Gladwell, M. (2008) The social life of paper. *The New Yorker*, March 25.

Godwin, M.A., and Schmidt, R.A. (1971) Muscular fatigue and learning a discrete motor skill. *Research Quarterly*, 42: 374–382.

Gragg, C.I. (1940) Because wisdom can't be told. *Harvard Alumni Bulletin*, October 19: pp. 78-84.

Hayes, J. R. (1989) *The complete problem solver* (2nd ed.). Hillsdale, NJ: Erlbaum.

Hempell, T. (2002) *What's Spurious, What's Real*? Measuring the Productivity Impacts of ICT at the Firm-Level. Mannheim: Centre for European Economic Research.

Hollingsworth, C.D. (1973) *A comparison of verbal and nonverbal instruction in elementary school mathematics*. PhD Dissertation. The Florida State University.

Imai, M. (1986) *Kaizen: The key to Japan's competitive success.* McGraw-Hill/ Irwin.

Jacobson, R. (1999) *Information Design*. Cambridge, MA: The MIT Press.

Jaffe, G. (2000) Pentagon cracks down on ... PowerPoint. *The Wall Street Journal*, April 25.

Jiang, P. and Fukuda, S. (2007) e-Manufacturing towards global engineering. *Journal of Manufacturing Technology Managment*, 18 (1).

Jonassen, D.H., Hannum, W.H. and Tessmer, M. (1989) *Handbook of task analysis procedures*. Praeger Publishers, New York.

Jonietz, E. (2007). TR10: Augmented Reality. *Technology Review*, March 12.

Katz, J. (2008). Engineering Jobs Top U.S. Skills Shortage List. *IndustryWeek*, April 25.

Kaufman, H.H., Wiegand, R.L. and Tunick, R.H. (1987) Teaching surgeons to operate – principles of psychomotor skills training. *Acta Neurochir*, 87: 1–7.

Ketikidis, P., Koh, L.S.C. and Gunasekaran, A. (2006) A special issue on e-technology manufacturing enterprise competitiveness. *Journal of Manufacturing Technology Management*, 17 (6).

Kidder, L.H. and Miller, S. (1991) What is "fair" in Japan? In H. Steensma and R. Vermunt (eds.) Social justice in human relations: societal and psychological consequences of justice and injustice, volume 2: 139 - 154. New York, NY: Plenum Press.

Lozano, S.C. and Tversky, B. (2006) Communicative gestures facilitate problem solving for both communicators and recipients. *Journal of Memory and Language*, 55: 47-63.

Liao, C., Guimbretière, F., Anderson, R., Linnell, N., Prince, C., Razmov, V. (2007) PaperCP: Exploring the Integration of Physical and Digital Affordances for Active Learning. In C. Baranauskas et al. (Eds.): *Human-Computer Interaction – INTERACT 2007* 11th IFIP TC 13 International Conference, Rio de Janeiro, Brazil, September 10-14, 2007, Proceedings, Part II, pp. 15 – 28.

Lin, X., Schwartz, D.L. and Bransford, J. (2007) Intercultural adaptive expertise: explicit and implicit lessons from Dr Hatano. *Human Development*, 50(1), 65-72.

Magill, R.A. (2004) *Motor learning and control*, (7th ed.) New York: McGraw-Hill.

Maskell, B. (1993) Why MRPII Has Not Created World Class Manufacturing and Where Do We Go From Here? *APICS*. September.

McGrath, J.E. (1993) Introduction: The JEMCO workshop: description of a longitudinal study. *Small Group Research*, 24, 285-306.

Melnyk, S. and Narasimhan, R. (1992) *Computer Integrated Manufacturing*. Business One Irwin, Homewood, IL

Mingers, J. (2004) Real-izing information systems: critical realism as an underpinning philosophy for information systems. *Information and Organization*, 14: 87-103

Monnoyer, E. (2003) What CEOs really think about IT. *The McKinsey Quarterly*, August

Newell, A. and Simon, H. (1972) *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.

OECD (2003) Seizing the benefits of ICT in a digital economy. Paris: Organization for Economic Co-operation and Development.

Olaniran, B.A. (1994) Group performance in computer-mediated and face-to-face communication media. *Management Communication Quarterly*, 7(3), 256-281.

Pathomaree, N. and Charoenseang, S. (2005) Augmented Reality for Skill Transfer in Assembly Task, In *Proceedings of 2005 IEEE International Workshop on Robots and Human Interactive Communication*, pp. 500-504.

Peter, J. and Valkenberg, P.M. (2006) Individual differences in perceptions of internet communication. *European Journal of Communication*, 21(2), 213-226.

Pogue, D. (2008) Digital pens to write on any paper. *The New York Times*, July, 3.

Powney, J., and Watts, M. (1987) *Interviewing in Education Research*. London: Routledge & Kegan Paul.

Prouty, K. (2000) Between ERP and a hard place. *The Plant Manager*, February.

Roberson, D., Davidoff, J., Davies, I.R.L. and Shapiro, L. (2004) The development of color categories in two languages: a longitudinal study. *Journal of Experimental Psychology: General*, 133 (4), 554-571.

Ross, J.W. and Weill, P. (2002). Six IT Decisions Your IT People Shouldn't Make. Harvard Business Review, November, 85 - 91.

Rubens, P. (2003) *Fax-the technology that refuses to die*. BBC News World Edition. December 15. Available on line: http://news.bbc.co.uk/1/hi/magazine /3320515.stm (accessed 25th June 2007).

Schaffer, B.S., and Riordan, C.M. (2003) A review of cross-cultural methodologies for organizational research: a best practice approach. *Organizational Research Methods*, 6: 169-215.

Schwartz, D., Bransford, J. and D. Sears. (2005) Efficiency and innovation in transfer. In J. Mestre (Ed.), *Transfer of learning from a modern multidisciplinary perspective.* CT: Information Age Publishing.

Schwartz, D. L. and Hartman, K. (2006) It is not television anymore: Designing digital video for learning and assessment. In R. Goldman (ed.) *Video Research in the Learning Sciences*. Erlbaum, Mahwah, NJ.

Schwartz, D. L. and Martin, T. (2004) Inventing to prepare for learning. *Cognition and Instruction, 22*, 129–184.

Schmidt, R.A. (1991) Frequent augmented feedback can degrade learning: evidence and interpretations. In J. Requin, G.E. Stelmach (eds.) *Tutorials in motor neuroscience*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 59–75.

Schmitz, J. and Fulk, J. (1991) Organizational colleagues, media richness and electronic mail. *Communication Research*, 18: 487-523.

Schwartz, D.L., Lindgren, R. and Lewis, S. (2009) Constructivism in an age of non-constructivist assessments. In T.M. Duffy, S. Tobias, Constructivist Instruction: Success or Failure? Routledge, New York.

Simon, S.J. (2001) The impact of culture and gender on websites. *The DATA BASE for Advances in Information Systems*, 32: 18-37.

Simpson, G.B. (1981) Meaning dominance and semantic context in the processing of lexical ambiguity. *Journal of Verbal Learning and Verbal Behaviour*, 20: 120-136.

Small, R., Yelland, J., Lumley, J., Rice, P.L., Cotronei, V., and Warren. R. (1999). Cross-cultural research: trying to do it better. 2: Enhancing data quality. *Australian and New Zealand Journal of Public Health*, 23: 390-395.

Snedeker, J., and Trueswell, J.C. (2004) The developing constraints on parsing decisions. *Cognitive Psychology*, 49: 238-99.

Sproull, L. and Kiesler, S. (1986) Reducing social context cues: electronic mail in organizational communication. *Management Science*, 32: 1419-1512.

Srinivasan, K. and Jayaraman, S. (1999) The changing role of information technology in manufacturing. *Computer*, 32 (3), 42-49.

Straub, D.W. (1994) The effect of culture on IT diffusion: email and fax in Japan and the U.S. *Information Systems Research*, 5: 23-47.

Stromnes, F.J. (1974) No universality of cognitive structures? Two experiments with almost-perfect one trial learning of translatable operators in Ural-Altaic and an Indo-European language. *Scandinavian Journal of Psychology*, 15, 300–309.

The Economist. (1995) The kindergarten that will change the world. *The Economist*, March.
Thun, J.-H., A. Gröbler, S. Miczka. 2007. The impact of the demographic transition on manufacturing. *Journal of Manufacturing Technology Management*, 18(8), 985-999.

Wierzbicka, A. (1992) *Semantics, culture, and cognition: universal human concepts in culture-specific configurations*. New York, NY: Oxford University Press.

Wurtz, E. (2005) *A cross-cultural analysis of websites from high-context cultures and low-context cultures*. Department of Design, Communication and Media, IT University Copenhagen.

Zerenler, M. (2007) Information technology and business performance in agile manufacturing: an emprical study in textile industry. *Proceedings of International Conference on Information Technology*, pp. 543-549.

PUBLICATION
III

Moveable factories: how to enable sustainable widespread manufacturing by local people in regions without manufacturing skills and infrastructure

Stephen Fox

Technology in Society, 42: 49-60
https://doi.org/10.1016/j.techsoc.2015.03.003

Technology in Society 42 (2015) 49–60

Contents lists available at ScienceDirect

Technology in Society

journal homepage: www.elsevier.com/locate/techsoc

Moveable factories: How to enable sustainable widespread manufacturing by local people in regions without manufacturing skills and infrastructure

Stephen Fox*

VTT, Technical Research Centre of Finland, Vuorimiehentie 3, Espoo, P.O. Box 1000, FI-02044 VTT, Finland

A R T I C L E I N F O

Article history:
Received 25 November 2014
Received in revised form 9 March 2015
Accepted 13 March 2015
Available online 31 March 2015

Keywords:
Moveable factories
Re-shoring/on-shoring/right-shoring/best-shoring manufacturing, sustainable manufacturing, advanced manufacturing, and distributed manufacturing
Base/Bottom of Pyramid

A B S T R A C T

Moveable factories enable high performance manufacturing. They carry their own power generation and are built to cover rough terrain. Hence, they have potential to enable more widespread modern manufacturing. In this paper, findings are reported from a study addressing two research questions. First, what goods should be produced by local people in regions without manufacturing skills and infrastructure? Second, how can lack of manufacturing skills and infrastructure be overcome? The study comprised literature review, semi-structured interviews, and structured questionnaire. Research participants are from Horn of Africa and from West Africa. All the goods that research participants considered to have potential for profitable production can be made with types of moveable factories that are available. Lack of local skills can be overcome through application of task design using proven techniques. In addition, techniques for designing capable production processes are applicable to moveable production. Established techniques for optimizing mix of production facilities, locations, and routes are also applicable. The robust mobility of moveable factories, and application of proven techniques, reduces the need for manufacturing infrastructure. Moveable factories are relevant to literature and debate concerning re-shoring/on-shoring/right-shoring/best-shoring manufacturing, sustainable manufacturing, advanced manufacturing, and distributed manufacturing. The relevance of moveable factories to these topics is analysed in terms of Resource-Based Theory, Knowledge-Based View, and Transaction Cost Economics.

1. Introduction

Without widespread modern manufacturing, countries can have a bi-polar distribution of income with few rich, many poor and little, if any, middle class. Traditional manufacturing of goods using rudimentary tools in subsistence economies is inefficient and cannot be scaled up. Hence, poverty is endemic [1]. Countries that base their economies on exporting their raw materials wealth rather than on widespread modern manufacturing do not generate a large middle class. Hence, poverty remains endemic [2]. Countries that off-shore manufacturing suffer a shrinking middle class. Hence, poverty becomes endemic [3]. However, centralized industrial manufacturing still leads to massive toxic waste and ecological destruction. Hence, pollution becomes endemic [4]. In this paper, research is reported that investigated potential for moveable factories to enable sustainable widespread modern manufacturing: in particular, by local people in regions without manufacturing skills and infrastructures.

The term, moveable factories, encompasses three types of production facilities that are designed and built to be operated efficiently at more than one location. Firstly,

---

* Tel.: +358 40 747 8801.
E-mail address: stephen.fox@vtt.fi.

http://dx.doi.org/10.1016/j.techsoc.2015.03.003
0160-791X/

individual mobile factories that are housed within a large van or are mounted on the back of a truck in a shipping container or similar. Individual mobile factories are suitable when there is one type of production needed at a location and when production location changes daily or weekly, for example, during the processing and packaging of agricultural harvests. Secondly, sets of mobile factories that can comprise several shipping container size factory units with complementary production capabilities, such as roof truss fabrication and door set assembly. These are suitable when production location changes monthly or yearly, for example, during the construction of a group of buildings. Thus, sets of moveable factories can be deployed as flexible manufacturing systems comprising specialist manufacturing cells that enable highly efficient production of particular components. Thirdly, modular factories that can comprise several pre-fabricated volumetric elements that are delivered by truck and are assembled to make one factory that is several times larger than a shipping container. These are suitable when production location can be fixed for up to several years and/or special internal environments are needed, for example, clean environments for production of goods containing microelectronics.

Only a few types of production that need special internal environments have to be wholly within a moveable factory. Such moveable factories may need to be longer and wider than the size of a shipping container. This is because of the need to have specially covered insulated floors, walls, and roofs; as well as enough internal working space for people. By contrast, many other types of moveable factory can have work carried out around them, as well as inside them. When production is better enabled by doing so, the sides of moveable factories can open out. Then, temporary external working floors and protective roof coverings can be used to expand the work space.

Moveable factories have been available for decades. They can cover rough terrain and carry their own power generation. Yet, their potential to bring about sustainable widespread modern manufacturing has gone largely unrecognized. This can be attributed to centralized industrial production having been the dominant paradigm in manufacturing since the Industrial Revolution. This has led to economic development being synonymous with centralized industrial development. Hence thus far, moveable factories have been used as an occasional production solution at locations where it is not viable to establish centralized industrial manufacturing. These locations include remote areas in rich countries where there is need for seasonal processing of forest berries and roaming livestock. In recent years, however, many very serious short-comings of centralized industrial manufacturing have become apparent. These range from excessive non-value adding transportation to limited potential to provide location-specific/person-specific goods [5,6]. Awareness of such short-comings calls into question whether economic development should continue to be synonymous with centralized industrial development.

The study addressed two research questions. First, what goods should be produced by local people in regions without manufacturing skills and infrastructure? Second, how can lack of manufacturing skills and infrastructure be overcome? The study comprised literature review, semi-structured interviews, and structured questionnaire. Research participants are from Horn of Africa and from West Africa. They are from two diaspora associations. This is because diaspora members have up-to-date knowledge of their homelands, and are often entrepreneurial with business in their homeland. Also, they seek opportunities to transfer knowledge from their diaspora country to their home land [7]. Semi-structured interviews were carried out separately with the chairpersons of the two diaspora associations. The semi-structured interviews led to the definition of different types of goods that the chairpersons considered could have potential for local manufacture in their home countries. The chairpersons' opinions were based on their frequent dialogues with diaspora members and with frequent contacts in their home countries, as well as their own ongoing investigations about potential business opportunities. Then, information about moveable factories was provided to diaspora association members during their separate association meetings. Next members completed a structured questionnaire. Alongside a list of goods compiled with diaspora association chairpersons, the question asked was: what kind of business opportunity is mobile/moveable factory for making: … There were a total of 25 respondents: 12 from Horn of Africa and 13 from West Africa. These were diaspora associations' members who have active interest in setting up businesses in their homeland and have up-to-date knowledge of demand and supply conditions.

The remainder of the paper comprises four sections: what goods should be produced; how lack of manufacturing skills and infrastructure can be overcome; relevance to global manufacturing objectives; and conclusions. Four global manufacturing objectives are considered. These are -shoring manufacturing; sustainable manufacturing, advanced manufacturing, and distributed manufacturing. The primary contribution to the literature is to explain how moveable factories can enable sustainable widespread modern manufacturing to be carried out by local people in regions without manufacturing skills and infrastructure. This contribution is relevant to scholars and practitioners in all countries seeking to increase employment and improve balance of trade. A second contribution is to the literature is explanation of how four global manufacturing objectives can be achieved better in practice with moveable factories. A third contribution is to the literature is to explain the potential of moveable factories better enable global manufacturing objectives in terms of three theoretical perspectives: Resource-Based Theory (RBT), Knowledge-Based View (KBV), and Transaction Cost Economics (TCE).

2. What goods should be produced

2.1. Types of goods

Research participants from Horn of Africa considered that the following types of goods could be made profitably with moveable factories: (1) leather goods, (2) housing blocks, bricks, lintels etc., (3) solar panels, (4) nails, bolts, brackets, handles, etc., (5) sheet roof panels, (6) fruit juice, tomato sauce, (7) water tanks and towers, (8) bread, biscuits, cakes. Research participants from West Africa considered that the following types of goods could be made profitably with moveable factories: (1) solar panels, (2) agricultural equipment such as poultry feeders, (3) food processing equipment such as maize grinders, (4) wind turbines, (5) rubbish handling equipment, (6) sanitation equipment, (7) furniture, (8) water tanks and towers. In these listings, (1) represents the goods considered to have highest potential for profitable production in moveable factories.

Differences between responses from the two respondent groups reflect different demand and supply conditions in their respective geographical regions. For example, Horn of Africa cattle herds provide a potential supply of leather for the manufacture of footwear, bags, etc. Similarly, current inefficient processing of agricultural crops was seen to offer opportunities for the mobile production of juices, sauces, bread, biscuits, etc. Also in Horn of Africa, there was considered to be unmet demand for building components needed in the local construction of houses. Many diaspora members were trying to arrange construction of houses for themselves and for others. They saw potential for the transfer of efficient western interlocking building component systems to their home countries.

By contrast, respondents from West Africa saw demand for more sophisticated goods that could be produced in moveable factories such as poultry feeders, maize grinders, and household furniture. These goods are already available to some extent, but they were considered to be of either bad quality or high price due inefficient traditional production methods. They also emphasized the demand for equipment to handle the ever increasing amounts of packaging waste that build up on the sides of streets, and the need for more sanitation equipment. In both regions, production and installation of solar panels were seen as being an important opportunity because of erratic electricity supplies. Similarly, in both regions, water tanks and towers were seen an important opportunity due to erratic water supplies.

The participants' responses were based on consideration of demand and supply conditions. For example, there was considered to be some unmet demand for portable diesel generators due to their price being too expensive for many households. However, the respondents considered that portable diesel generators were not a good opportunity because of the difficulty of trying to produce at lower prices than mass produced Asian imports. By contrast, the sizing, framing, and installation of solar panels could be carried out more efficiently with moveable factories. Similarly, there was considered to be some unmet demand for water pumps, but the business opportunity was considered to be in the sizing, framing, and installation of water tanks and towers.

The participants were mindful of the difficulties of establishing a profitable income stream for some types of goods. For example, they were certain that individual households would pay directly for the installation of household-specific solar panels and water tanks. However, they were not certain that individual households would contribute proportionally to shared solar panels and water tanks – even though large panels and tanks could be cheaper to purchase and more efficient in operation. West African respondents saw rubbish handling as being a very urgent problem that could be addressed with equipment such as sorting bins and recycling equipment. These could be made in moveable factories. However, participants could not envisage who would pay for such goods. One participant made enquiries with the local council of his home town. He was informed that while the local council saw the build-up of rubbish as being a major problem in need of an urgent solution, they were unsure how sorting and recycling could be funded. Similarly, better sanitation was required in public spaces but they were unsure how funding could be obtained, for example, to provide and to empty watertight septic tanks.

With regard to validity and generalizability of the findings, it can be seen that the differences in population density and per capita GDP are reflected in the types of goods seen as having potential for profitable production. In particular, the population density of the West African respondents' homeland is twice that of Horn of Africa respondents'. Also, the per capita GDP of West African respondents' homeland is four times higher than that of Horn of Africa respondents'. Accordingly, construction goods were seen as opportunities by Horn of Africa respondents from regions in need of less rudimentary housing. By contrast, challenges of waste handling and public sanitation were seen as important to West African respondents. This is because their home towns were suffering from increasing build-up of waste from food packaging and consumer goods packaging.

2.2. Potential for moveable factory production

All of the goods that participants considered to have potential for profitable production can be made with moveable factories. A few mobile factories are already in use for agricultural production. For example, a mobile fruit processing factory is used in the Yumbe Region of Uganda. In one working week, this is used to process more than 20 tonnes of mangoes. A particular advantage of mobile production is that it is possible to accumulate large outputs from small contributions: in this case, local people with just one or two mango trees can carry their fruit harvest the short distance to the mobile factory as it passes by. This enables all crops to be utilized instead of only those grown on large farms [8].

With regard to moveable bakery factory, the World Health Programme has already introduced a moveable factory will produce nutritious biscuits for school meals programmes in Afghanistan. The biscuit factory comprises seven containers each measuring 6 × 2.5 m. The moveable factory is has to been designed to take into account Afghanistan's climate of intense summer heat and sub-zero winters. The moveable factory enables mixing, cutting, and packaging of biscuits containing micronutrients vital for children's growth. The factory provides work for at least twenty-five local people per working shift [9].

A wide range of small scale production equipment is available to support production of building components. For example, semi-automated equipment are commercially available for making components such as nails, screws, brackets, concrete blocks, metal lintels, roof trusses, corrugated sheet roofing and roof tiles. There are no fundamental barriers to combining such equipment in efficient layouts within and around sets of moveable factories [10].

Production equipment for cutting and sewing leather into bags, sandals etc., is commercially available and can be combined in efficient layouts within moveable factories. Similarly, production equipment is commercially available for the sizing, framing, and installation of solar panels. In particular, solar panels can be built up from small solar cells (e.g. 150 mm × 150 mm) and framed using basic handheld tools for cutting and drilling glass sheets and metal sections. There are no fundamental barriers to combining such equipment in efficient layouts within and around moveable factories [11].

Also, the production equipment needed for fabrication of furniture, maize grinders, poultry feeders, septic tanks, small wind turbines, water tanks, water towers, includes conventional tools for the cutting, drilling, riveting, and fixing of sections of conventional materials such as metal and wood. For examples, water tanks can be fabricated from corrugated steel sheet. Thus, a machine for producing corrugated roof sheeting can be also used for producing sheets to be used in the fabrication of water tanks. Mobile factories for fabrication work are already used at some remote construction site locations and at disaster locations, for example, to erect shelters as quickly as possible [12]. The most sophisticated mobile factories contain digitally-driven advanced manufacturing equipment that can be used to produce complicated machine parts. Accordingly, it is also possible to produce equipment for waste handling such as compactors, as well as simpler equipment such as sorting bins [13].

Currently, moveable factories cost tens of thousands or hundreds of thousands of e.g. US dollars; rather than the tens or hundreds of millions that large fixed factories cost [8]. However, moveable factories are currently designed and fabricated as individual engineer-to-order capital goods. When demand for moveable factories increases, their costs can be reduced through application of well-established techniques for increasing production efficiency in response to increased demand [14]. Further cost reductions can be achieved by fabricating moveable factories in their country of use, rather than shipping them. Countries that already have an engineering sector, such as South Africa, have potential to produce moveable factories immediately. For other countries, an initial step to developing the capacity to make their own moveable factories, and at the same time reduce shipping costs, is to have them imported as kits for local assembly. A summary of types of goods to be produced and moveable factory solutions is provided in Table 1.

3. How lack of manufacturing skills and lack of infrastructure can be overcome

3.1. Overcoming lack of skills

The goods that participants considered to have potential for profitable production cover the range of production processes from material conversion (e.g. processing fruit into juice) to the fabrication of capital goods (e.g. fabricating diverse components into waste handling equipment). Different production processes require different amounts of human labour. For example, material conversion often requires labour only for the input of raw materials (e.g. fruit) and the handling of formed outputs (e.g. juice). By contrast, the fabrication of capital goods is more labour intensive because of the need to form components and then put them together in complicated structures. At the same time, more skills and more infrastructure are needed to enable the local fabrication of capital goods. This is because of the diversity of tasks involved and the diversity of the components needed at the work location.

Typically, materials conversion operations require few skills. Thus, lack of skills is not a barrier for such production. For example, a mobile fruit processing factory used in the Yumbe Region of Uganda is used to more than 20 tonnes of mangoes convert per week into fruit juice. Local people bring their mangoes to the mobile factory and collect the mango juice. This enables much higher mango crop utilization and local people to increase their incomes even if they have only a small number of mango trees [8]. The essential skill is the maintenance of the processing machinery in the mobile factory. However, this maintenance work is no more challenging that the electrical, hydraulic, and mechanical maintenance required to keep trucks driving across the rough terrain that is common in countries lacking complete road infrastructure.

Table 1
Types of goods and moveable factory solutions.

Type of good	Moveable factory solution
Processed agricultural produce (e.g. fruit and vegetables into juices and sauces; fish, meat, poultry into cuts).	Individual mobile factories housed within one large van or mounted on back of truck, for daily or weekly moving of production location. Temperature controlled internal working environment for extreme climatic conditions.
Basic engineered goods (e.g. nails, screws, brackets; concrete blocks, roof tiles; metal lintels, roof trusses, corrugated sheet roofing; water tanks, water towers).	Sets of moveable factories for monthly or yearly change of production location. Can be used as specialist manufacturing cells, which enable highly efficient production of related components, in a flexible manufacturing system.
Sophisticated goods (e.g. special foodstuffs with added micro-nutrients; consumer electronics such as computer tablets; medical goods such as implants and prosthetics).	Pre-fabricated modular factory elements for less frequent change of production location. Can provide clean environments.

For types of production that traditionally require more skills, task design can be applied to overcome skill shortages. This is widely applied by global companies, such as Toyota, to enable consistent productivity and quality wherever they set-up production. Task design involves analysis of the mental and physical steps in performing a task [15]. These steps are rationalized systematically to reduce their number and their variation. This is achieved through methods such as jigs, design for manufacture and assembly (DFMA), and visual control. Jigs and other forms of physical templates are used to ensure consistent positioning of work pieces, and/or motion of tools during production [16]. DFMA involves applying principles, such as "design parts to be self-aligning and self-locating", to enable anybody to carry out assembly correctly and quickly [17]. Visual control involves, for example, visual instructions that do not rely on words for the communication of meaning [18]. Application of such techniques results in successful task execution not relying on prior skills. This is because of the replacement of task complexity with task simplicity.

Consider, for example, traditional skills training for carpentry and joinery compared to skills training for assembling an IKEA cupboard. Traditional skills training for carpentry and joinery involves trying to learn over many years how to carry out a wide range of tasks with many different materials and many different tools in many different situations to make many different types of products with many different specifications. Some of these combinations of materials, tools, situations, and products may occur once during an apprenticeship and then not again for many years. Conversely, many of these combinations of materials, tools, situations, and products never occur during an apprenticeship. Furthermore, there is unpredictable variation in the characteristics of materials, tools, situations, and specifications. This unpredictability severely limits the potential for transfer of learning into practice [19].

The challenges of addressing such complexity result in persistently low productivity and quality in, for example, the construction industry [20]. By contrast, the skills training for assembly of an IKEA wardrobe involves looking at visual instructions. Then, using a few standard tools and fixings, joints are put together that have been designed for ease of assembly. In particular, the assembly of IKEA wardrobe is designed to be a simple task comprising minimum steps with minimum variation.

Thus, while traditional skills training aims to enable open-ended task complexity to be addressed as best as is possible across diverse situations and specifications, task design succeeds in enabling anybody anywhere to achieve good results within a narrow and predictable range of steps. Task design, however, is not limiting. This is because an evolving increasing number of tasks can be enabled through job design. This involves specification of contents, methods and relationship of work in order to improve work performance and job satisfaction [21]. Thus, a person can learn very quickly how to execute one designed task to a high standard. Then, that same person can learn quickly how to execute a second designed task to a high standard, and so build up a repertoire of skills while achieving high performance from the outset.

Task design and job design can be used within broader practices, such as Six Sigma, that increase process capability. This is appropriate because in order for the production of goods to always conform to customer requirements, all contributing processes need to be capable. Outputs from capable processes conform to requirements reliably and consistently. By contrast, outputs from processes that are not capable often do not conform to requirements. Incapable processes can lead to scrap, rework, warranty claims, loss of goodwill, etc. The capability of processes should be assessed during their development. In the production of physical goods, processes comprise tasks, and the production facilities, materials, methods, and people involved in carrying them out. If assessment reveals that a process is incapable, that process should be improved until reassessment indicates that it is capable [22].

Hitherto, consistently high productivity and quality across the world has been dependent upon global companies having fixed production facilities, such as a Toyota factory. Nonetheless, task design, job design, and Six Sigma are equally applicable to moveable factories. The number of tasks related to one moveable factory will certainly be less than in a large fixed factory. However, as outlined above, moveable factories can be used together as flexible manufacturing systems [6].

Any country that teaches engineering has people who can apply task design, job design, Six Sigma and related techniques. Only a few engineers are needed to enable many local people to be able to work in high performance production using moveable factories. If there are any countries that do not have any higher education institution teaching engineering, employing a few foreign engineers to kick-start moveable production is a small step to enabling many local people to have productive work. However, many parts of the world without industrial manufacturing infrastructure do have engineering education. Sometimes, their problem is not lack of engineering education, but lack of work in the home country for their qualified engineers to do. For example, in 2014, the Palestine Polytechnic University Department of Engineering offers courses in several disciplines that are directly relevant to the design and operation of moveable factories including: automotive engineering; mechatronics engineering; and refrigeration engineering. A summary of skill solutions is provided in Table 2. As discussed below, there are also many practical solutions for addressing lack of industrial manufacturing infrastructure.

3.2. Overcoming lack of infrastructure

Key to process capability is having the necessary materials available for production where and when they are needed. Lack of transportation infrastructure could hinder the delivery of materials. On the other hand, the mobility of moveable factories has potential to make the supply of materials less challenging than supply of materials for fixed factories. Consider, for example, the processing and packaging of agricultural products. Within conventional industrial manufacturing, vehicles travel to the locations of farms to collect crops, livestock, etc. Then, the vehicles travel to a fixed factory location where the agricultural outputs are

Table 2
Skill and infrastructure solutions for different types of goods.

Type of good	Skill solution	Infrastructure solution
Processed agricultural produce (e.g. fruit and vegetables into juices and sauces; fish, meat, poultry into cuts)	Typically, materials conversion operations require few skills. Essential skill is maintenance of processing machinery, but this is no more challenging that the electrical, hydraulic, and mechanical maintenance required for trucks	Mobile factories carry out production at agricultural locations. This reduces need for paved roads, number of journeys, animal suffering, and post-harvest losses. Use of large dispensing/vending stations can further reduce journeys, and eliminate packaging materials, work, and waste
Basic engineered goods (e.g. nails, screws, brackets; concrete blocks, roof tiles; metal lintels, roof trusses, corrugated sheet roofing; water tanks, water towers) Sophisticated goods (e.g. special foodstuffs with added micro-nutrients; consumer electronics such as computer tablets; medical goods such as implants and prosthetics)	Task design, job design and Six Sigma using widely proven successful techniques, such as jigs, DFMA, visual control, to replace endemic production complexity with repeatable production simplicity, which is not dependent upon production personnel having prior education, training or experience	Design of production processes for reliable consistent capability through maximising the value that is added locally by local people using versatile basic materials such as sheet metal and metal hollow sections -rather than import of large volumetric components which already have had value added by centralized and foreign production. Optimization of moveable factory mix, routes and location with widely applied proven optimization techniques

processed and packaged. Subsequently, more vehicles travel along more roads to wholesalers and retailers to deliver packaged goods. By contrast, mobile factories can go the where the agricultural outputs are and process them where they are. This introduces many ecological and economic advantages. For example, the transportation of livestock leads to "shipping fever" (i.e. Bovine Respiratory Disease). In addition to the suffering of the animals being transported, associated annual financial losses amount to billions of e.g. US dollars [23]. Such disadvantages from transportation are not restricted to livestock. Post-harvest losses to fruit and vegetables are also extremely wasteful and very costly [24]. In addition, widely distributed local processing can prevent the ecological problems caused by large-scale concentration of effluents and other wastes at a centralized production location. Thus, much suffering, waste, and cost can be eliminated through use of mobile factories.

Distribution of agricultural goods processed in mobile factories can be carried out by mobile factories. Further supply chain simplification can be achieved through the use of alternatives to single serve packaging that is advocated for developing countries, but generates so much packaging waste [25]. For example, milk vending machines are already being widely used across Europe. These enable large amounts of milk to be placed in one large container for people to draw from always using the same bottles etc. Such vending machines can be also used for juice, sauces, etc. The majority of vending machines components could be made with moveable factories. In addition, necessary energy for them could be provided solar panel arrays fabricated with moveable factories. Thus, rather than having the ever increasing problem of trying to collect, sort, recycle packaging waste, the whole supply chain can be simplified by not producing packaging to begin with [26]. Clearly, the farther agricultural production is from major centres of human population, the farther the distances that have to be travelled to bring agricultural produce to consumers. However, there is far more transportation infrastructure on major routes to major centres of population than in rural areas [27].

Unlike the processing of agricultural outputs, the production of consumer goods and capital goods using moveable factories is more dependent upon the delivery of materials. This can be simplified by not transporting volumetric components. For example, rather than transporting a small quantity of formed plastic water tanks, enough flat metal sheets and rectangular hollow metal sections can be transported to make many water tanks and many water towers. Flat metal sheets can be formed in-situ to make corrugated metal sheets that can be used for roof coverings and for water tanks. In addition, flat metal sheets and hollow metal sections can be used to make brackets, lintels, frames and casings for vending machines, hoppers and stands for maize grinders, solar panel arrays, etc.

This example illustrates how transportation of materials to the location of moveable factories can be simplified and minimized by designing production processes to maximise the value that is added locally by local people. Similarly, the delivery of flat timber sections can enable local production of a wide variety of value-added goods ranging from roof trusses to household furniture. Importantly, the production of consumer goods and capital goods is more likely to be carried out at one location for several months. This is different to mobile agricultural processing that can move daily. Accordingly, there is potential to hold some stocks of production materials, and so avoid total dependency on deliveries arriving at one particular time.

Moveable factories are equipped with their own diesel generators and can carry solar panels to also generate energy. Nonetheless, optimization of routes and locations for moveable factories is important. This can be achieved using well-established techniques, such as the load-distance method. This is because the optimization of routes and locations has long been a focus in many sectors including commercial aviation, out-of-town retailing, and road haulage. Common to optimization techniques is the balancing trade-offs between proximity to customers, suppliers, and other key constraints such as route access which can be determined by climatic, legal, political, and/or military factors. These techniques are also well-suited to determining the optimum mix of mobile factories, sets of moveable factories and modular factories. This is because the composition of value chains is also an established topic in many sectors. For example, it has long been important to determine the best mix of large, medium, and small aircraft that should be operated by an airline; and how many heavy, medium, and light trucks should be operated by a road haulier [28].

Overall, moveable production should be designed for process capability that reliably and consistently meets customer requirements. An example of how systematic design of overall processes, and every task within them, can achieve remarkable productivity and quality is the use of fertigation systems. These enable people without prior agricultural work experience to achieve world class crop yields in desert regions. Fertigation systems deliver to plants only the small amount of water and nutrients needed for flourishing. Water and nutrients are delivered with pin-point accuracy through short pipes that are push-fit together to exact overall lengths. As with all processes systematically designed to be capable, the high performance of this system is highly predictable and highly repeatable. For example, by immigrants to the Middle East and local people in India's Rajasthan desert area [29].

All of the factors discussed about are summarized in Fig. 1. This diagrammatic summary illustrates that multiple factors can be brought together through process design to enable sustainable widespread manufacturing in regions without manufacturing skills and infrastructure.

4. Relevance to global manufacturing objectives

Moveable factories are relevant to four global manufacturing objectives as follows: shoring manufacturing (i.e. re-shoring/on-shoring/right-shoring/best-shoring), sustainable manufacturing, advanced manufacturing, and distributed manufacturing. These objectives have emerged in response to societal challenges including lack of middle class jobs and escalating pollution [2–4]. In this section, it is explained how moveable factories can better enable shoring sustainable manufacturing without reliance on highly advanced distributed manufacturing technologies. Resource-Based Theory (RBT), Knowledge-Based View (KBV), and Transaction Cost Economics (TCE) are referred to throughout. Within RBT, advantage arises from having resources that are difficult to imitate or substitute [30–32]. Within KBV, advantage arises most from knowledge because, especially when tacit, knowledge can be the resource that is most difficult to imitate or substitute [33]. Within TCE, advantage arises from determining how best to combine internal resources and external resources [34,35]. RBT, KBV, and TCE have their origins in research carried out in the 1930s [36]. Over the subsequent decades, further research has revealed the limitations of initial research; and the three perspectives have been developed. There has been much scholarly debate about the three perspectives. However, they have not been integrated into a single theory; and none of them has become dominant [37,38]. Accordingly, each perspective continues to be applied widely in the analysis of production innovation [39,40].

4.1. Re-shoring/on-shoring/right-shoring/best-shoring manufacturing

Countries that have previously off-shored manufacturing, such as USA and UK, have initiatives to revitalize their manufacturing sectors. The term, re-shoring, is being used to describe companies bringing back much the same manufacturing as they have earlier off-shored to other countries with lower labour costs. The term, on-shoring, is more open to setting-up completely new manufacturing. Other terms, such as right-shoring and best-shoring, draw attention to the need for careful analysis of factors when determining the optimum balance of production on-shore and production off-shore. Debates about “shoring” are public and political, as well as technological and industrial [41]. For example, initiatives to on-shore manufacturing by local companies in emerging economies has involved politicians arguing that their nations' dependency on exporting raw material wealth to China and importing Chinese manufactured goods is a form of neo-colonialism [42,43].

Much recent literature about the economic development of such countries has been framed in terms of the Base/Bottom of the Pyramid (BOP). This has encompassed microcredit (e.g. lending tiny sums of money to poor people); products for very poor (e.g. shampoo in single serve sachets); adoption of innovations (e.g. mobile banking); venture capital (e.g. lending to SMEs); brand awareness (e.g. to influence product adoption); business—community partnerships (e.g. community services using branded products). Overall, the BOP proposition is that billions of poor people can become less poor by brand companies making a fortune from selling them billions of low value products, while they retain production resources (RBT) including production expertise (KBV). Moreover, brand companies determine the structures, relationships, and activities that govern economic exchange (TCE) [44]. Here, an alternative has been explained: widespread modern local production by local people. This local adding of value can establish polycentric internal markets that are not dependent upon the export of raw materials wealth to foreign countries; and are not dependent on the import of completed goods from foreign countries. Thus, local people can create their own prosperity instead of making a fortune for global brands. It has been explained that assumed barriers to widespread modern manufacturing can be broken down by moveable factories and with proven production capability design techniques. All the necessary technologies (RBT) and techniques (KBV) are available to today. The goods that they have identified as having potential for profitable moveable production are not sophisticated. However, there is no reason why moveable factories and rigorous process design cannot enable local production of more sophisticated goods [6]. For example, local production of computer tablets has been set up successfully in Haiti [45]. The advantage of moveable factories is that they facilitate widespread fast-set up of reliable and consistent high performance production at lower cost (TCE).

Moveable factories can locate production precisely where and when needed. Nonetheless, although the fundamental issue in “shoring” debates is optimizing

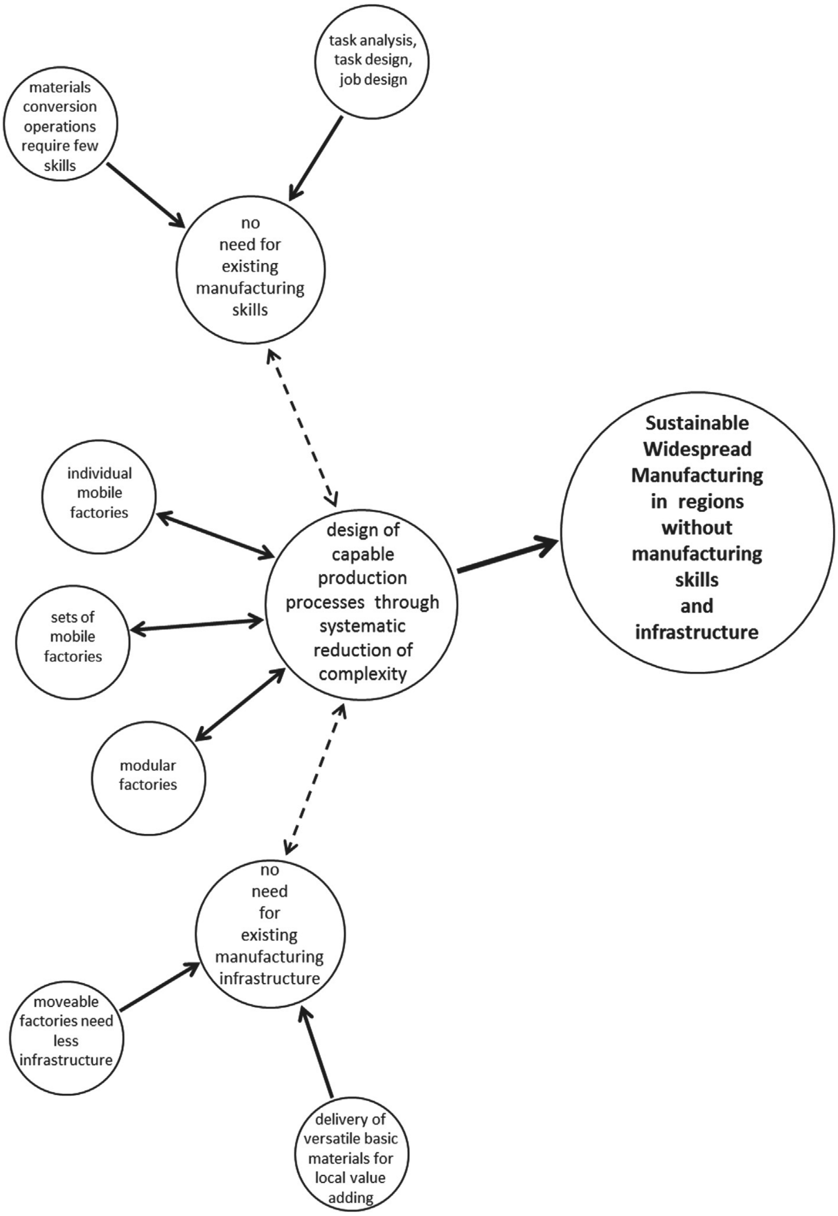


Fig. 1. Summary of enabling factors.

production location, the debate has not encompassed moveable factories. Rather, the debate is focused upon in which countries to locate centralized industrial production, and how to make such production more environmentally friendly [46–48]. However, as discussed above, centralized industrial production is inherently environmentally unfriendly because, for example, it fosters disease in agricultural production; and generally involves extensive transportation that does not add value (TCE). Moreover, centralized industrial production can only bring employment to some areas of large countries with thinly distributed populations, such as Australia, Brazil, and Russia. Hence, moveable factories should be included in debate about best-shoring.

4.2. Sustainable manufacturing

Large fixed factories polluting factories, in countries such as China, cannot be shut down easily without setting-up alternative sources of employment. Within the established paradigm of centralized industrial production, replacing large fixed polluting factories with new cleaner large fixed factories takes many years. Also, it involves the permanent designation and digging up of more land for industrial purposes. Moreover, it involves massive capital investment. To recover the capital and interest costs of massive investment, large fixed factories must be operated continually at close to their maximum capacity. This, in turn, depends upon encouraging the throwaway consumerism of people continually buying new goods - whether they need them or not. Two strategies for achieving this are planned obsolescence of desirability, through regular mass marketing of new styles; and planned obsolescence of function through offering whole new goods rather than updated replacement parts. Thus, although polluting emissions may be reduced by cleaner large fixed factories, a principal cause of environmental unsustainability persists: the pushing up of consumption to recover high capital investment costs [49–51]. It is important to note that much of high capital investment costs do not add value to the manufacturing process. For example, the high costs of buying land and ground engineering is not essential when manufacturing can be mobile. Thus, much of the fixed resource costs (RBT) and fixed knowledge costs (KBV) that drive up the costs of manufactured goods (TCE) are actually costs of real estate and building construction: rather than manufacturing costs.

Furthermore, focussing on application of ever more advanced technologies cannot enable socially sustainable manufacturing. This is because technological advanced manufacturing cannot in itself bring about the effects of meeting the needs of people and enabling people to express their potential [52]. The focus on advancing manufacturing technology since the Industrial Revolution has left people's essential needs unmet in many parts of the world. It has erected high barriers to people expressing their potential as production work has relied on ever higher investment (RBT) and higher education (KBV). Moreover, advanced manufacturing technologies are slow to set-up. Consider, for example, the need to enable rapid reconstruction in countries seeking to achieve demilitarization. Here, the initial emphasis is upon the optimum processing and distribution of local foodstuffs, and upon the rapid construction of essential buildings [53]. Then and thereafter, there is need for manufacturing to be carried out locally by local people within their different ethnic groupings. This is a more socially sustainable alternative to setting-up centralized manufacturing in nation states that have strongly different ethnic groupings, which were corralled together by imperialist force [54]. As described above, these reconstruction and ethnic imperatives can be addressed immediately through the combination of moveable factories (RBT) and process capability design techniques (KBV).

4.3. Advanced manufacturing

The emphasis in advanced manufacturing literature and practice is advanced technologies, such as new materials, intelligent robotics, and smart systems. Focus on advanced technologies is seen as being necessary to off-set higher labour costs in rich countries and to make manufacturing more environmentally sustainable [55–58]. However, new materials, intelligent robotics, etc., erect even higher barriers to sustainable local manufacturing by local people. These barriers are financial and educational. For example, few companies have the money to pay for intelligent robotics (RBT) and few people have sufficient education to set-up intelligent robotics (KBV). Thus, advanced manufacturing is a continuation of the trend since the Industrial Revolution for the set-up of manufacturing to require ever higher capital investment and ever higher education. This, in turn, continues the trend to drive up consumption to recover the very high costs of technological development and set-up (TCE). Moreover, in many markets, these barriers enable the structures, relationships, and activities that govern economic exchange to be determined by a relatively few companies (TCE).

Hence, while advanced technologies can offer some advantages for some specialized types of manufacturing, they are neither necessary nor sufficient to advance widespread modern manufacturing by local people. By contrast, the major reductions in non-value adding transportation offered by moveable factories can off-set higher labour costs as well as reduce transportation pollution. Moreover, their low investment costs (RBT) obviate the need to continually drive up consumption that drives ecological destruction. Moveable factories with established technologies bring high performance manufacturing to diverse locations including those with challenging temperatures, rough terrain, and little infrastructure. This is done without any need for new materials, intelligent robotics, or any other technologies that erect higher barriers to widespread local production by local people. Accordingly, the explanation provided in this paper calls into question the strong focus of advanced manufacturing on advanced technologies.

4.4. Distributed manufacturing

Recent literature concerned with distributed manufacturing has been focused upon emerging digital technologies, including: Internet, virtual reality, and digital manufacturing technologies such as 3D printing [59–61]. The potential to enable more sustainable development through such distributed digital technologies has been a topic of interest [62]. Some propositions about distributed manufacturing, based on emerging technologies, fall within the genre of techno-futurism that resorts to extreme predictions to attract attention. These include a world populated by self-replicating fully automated machines that produce their own spare parts and spread themselves indefinitely in an ever expanding self-aware network [63]. However, the potential to achieve sustainable development immediately by combining moveable factories with production process design techniques has been largely overlooked [5]. This paper provides explanation of that potential, and so expands the literature concerned with distributed manufacturing.

In particular, moveable factories costs tens of thousands or hundreds of thousands of e.g. US dollars; rather than the tens or hundreds of millions that large fixed factories cost

Table 3
Relevance of moveable factories.

Topic	Relevance	Theoretical perspective
Reshoring/on-shoring/right-shoring/best-shoring	Current literature and debate about re-shoring, on-shoring, right-shoring, and best-shoring is about optimizing the location of largely centralized production using advanced technologies. This overlooks the potential of moveable factories to optimize production location with much greater precision. In emerging economies, moveable factories can enable polycentric internal markets that are not dependent upon foreign companies, brands, single serve, and other BOP pillars.	Within current literature and debate about shoring manufacturing, production resources (RBT), including production expertise (KBV) are retained by companies that determine the structures, relationships, and activities that govern economic exchange (TCE). However, all the necessary moveable factory technologies (RBT) and techniques (KBV) are available today to enable local people to have much more influence over the structures, relationships, and activities that govern economic exchange (TCE).
Sustainable manufacturing	Current literature and debate about reducing industrial pollution relates to replacing old centralized dirty factories with new centralized cleaner factories that use ever more advanced technologies. This is not environmentally sustainable because the financial imperatives to drive up consumption are perpetuated. It is not socially sustainable because high educational and financial barriers to local production by local people are perpetuated.	Much of the high capital investment costs of large fixed factories do not add value to the manufacturing process when manufacturing can be mobile. Rather, much of the fixed resource costs (RBT) and fixed knowledge costs (KBV) that drive up the costs of manufactured goods (TCE) are actually the costs of real estate and building construction. These costs are recovered by more non-essential costs such as marketing to drive up consumption.
Advanced manufacturing	Current literature and practice focus is advanced technologies such as new materials and intelligent robotics. These are neither necessary nor sufficient to advance globally sustainable manufacturing. Moreover, they are a continuation of the trend since the Industrial Revolution to erect ever higher barriers to manufacturing.	Few companies have enough money to pay for intelligent robotics (RBT) and few people have sufficient education to program them (KBV). In many markets, these barriers enable the structures, relationships, and activities that govern economic exchange to be determined by a relatively few companies (TCE).
Distributed manufacturing	Current literature has distributed manufacturing as a future goal based on emerging technologies. Moveable factories enable high performance distributed manufacturing immediately.	Moveable factories have the advantages of lower factory costs and faster cost recovery (RBT), simpler supply chain management (KBV), and lower waste costs due to higher operating flexibility (TCE).

(RBT) [8]. Secondly, they can be set-up in months rather than years, and costs can be recovered much more quickly (RBT). Thirdly, they do not require the permanent designation and digging up of land for industrial purposes (RBT). Fourthly, as discussed above, moveable factories can reduce the need for heavy financial investments in supply, storage, distribution, and sales facilities (RBT). Fifth, much less education is required to operate moveable factories and their simpler supply chains (KBV). Sixth, moveable factory can be adapted and arranged for different combinations of manufacturing at different locations. This location flexibility can reduce post-harvest losses and other non-value-adding costs, which can contribute to higher prices (TCE). Hence, moveable factories offer much lower financial investment burden, much faster return on investment, much lower opportunity costs, and much greater investment flexibility (RBT). As a result, moveable factories can remove financial imperatives to push up consumption (TCE). For all of these reasons, moveable factory production is highly relevant to the challenges of countries needing to reduce unsustainable centralized industrial manufacturing, and transition to distributed manufacturing. Thus, centralized industrial manufacturing cannot be considered always to be the best option for manufacturing. Rather, centralized industrial manufacturing should be considered as being the only option when massive industrial processes are needed, such as the conversion of ore into steel.

A summary of the relevance of moveable factories to these topics is provided in Table 3.

5. Conclusion

Findings have been reported from a study that addressed two research questions. First, what goods should be produced by local people in regions without manufacturing skills and infrastructure? Second, how can lack of manufacturing skills and infrastructure be overcome? The research has involved diaspora association members who seek to establish enterprises in their home countries. They have up-to-date knowledge of demand and supply conditions in their home countries through frequent communication and regular visits. Findings indicate that goods with potential for profitable production can be made with moveable factories; and that lack of manufacturing skills and infrastructure are not fundamental barriers to doing so.

The primary contribution to the literature is to explain how moveable factories can enable sustainable widespread modern manufacturing to be carried out by local people in regions without manufacturing skills and infrastructure. This contribution is relevant to scholars and practitioners in all countries seeking to increase employment and improve balance of trade. A second contribution is to the literature is explanation of how four global manufacturing objectives can be achieved better in practice with moveable factories. A third contribution is to the literature is to explain the potential of moveable factories better enable global manufacturing objectives in terms of three theoretical perspectives: Resource-Based Theory (RBT), Knowledge-Based View (KBV), and Transaction Cost Economics (TCE).

This contribution is timely as many of the world's population still do not have access to the resources required to create their own prosperity. This is the case for millions of teenagers trying to survive in regions without any source of employment. It is the case for subsistence farmers trying to survive amidst violent political conflict. It is the case for mothers trying to survive with their children in overcrowded refugee camps. Today, none of these people have access to the resources required to create their own prosperity. This is because the means of creating prosperity are still operated at centralized locations behind high educational and financial barriers. So it remains that the poverty of previous millennia persists in the twenty-first century. However, as explained in this paper, there is no fundamental reason why moveable factories cannot be brought profitably to regions that currently lack the resources to create their own prosperity. Financial barriers are low, and educational barriers are even lower. Hence, there are many opportunities to make needed products, new employment, and improved conditions for peace.

References

[1] Waters T. The persistence of subsistence agriculture: life beneath the level of the marketplace. Lanham, MD: Lexington Books; 2007.
[2] McGroarty P. Poverty still plagues South Africa's Black majority. Wall Str J 2014; December 8.
[3] Hope Y. 4 in 5 in USA face near-poverty, no work. USA Today; 2013; September 17.
[4] Kahn J, Yardley J. As China roars, pollution reaches deadly extremes. The New York Times; 2007; August 26.
[5] Fox S. Third wave Do-It-Yourself (DIY): potential for prosumption, innovation, and entrepreneurship by local populations in regions without industrial manufacturing infrastructure. Technol Soc 2014;39: 18–30.
[6] Jackson M, Wiktorsson M, Bellgran M. Factory-in-a-box: demonstrating the next generation manufacturing provider. In: Mitsuishi M, Ueda K, Kimura F, editors. Proceedings of the 41st CIRP conference on manufacturing systems, Tokyo, Japan, May 26–28; 2008. p. 341–6.
[7] Plaza S. Mobilizing the Diaspora: creating an enabling environment for trade, investment, knowledge transfer and enterprise development. In: Raj Bardouille, Muna Ndulo, Margaret Grieco, editors. Africa's finances: the contribution of remittances. UK: Cambridge Scholars Publishing; 2008.
[8] http://caes.mak.ac.ug/news-a-events/latest-news/1412-makereres-mobile-fruit-factory-launched-in-yumbe.html.
[9] Kennedy FA. Mobile biscuit factory heads to Afghanistan. World food programme, via Cesare Rome. 2012: July 27.
[10] For example: http://www.diversegroup.co.za/corrugatedIBR.php; http://www.zhauns.com/nail.php.
[11] Hurley P. Build your own solar panel: generate electricity from the sun. Wheelock VT USA: Wheelock Mountain Publications; 2012.
[12] http://www.howickltd.com/applications/mobile-factory.
[13] Ikstrums A. The US army's mobile parts hospitals. Defence Industry Daily; 2010, March 29.
[14] Haug A, Ladeby K, Edwards K. From engineer-to-order to mass customization. Manag Res News 2009;32:633–44.
[15] Ayoub MM, Dempsey PG. The psychophysical approach to manual materials handling task design. Ergonomics 1999;42:17–31.
[16] Henriksen EK. Jig and fixture design manual. New York, N.Y.: Industrial Press Inc; 1973.
[17] Boothroyd G, Dewhurst P, Knight W. Product design for manufacture and assembly. 2nd ed. New York: Marcel Dekker; 2002.
[18] Ortiz CA, Park M. Visual controls: applying visual management to the factory. New York, NY: CRC Press; 2010.
[19] Ellis HC. The transfer of learning. New York: The Macmillan Company; 1965.
[20] Teicholz P. Labor-productivity declines in the construction industry: causes and remedies (another look). AECbytes View Point#67. 2013: 14 March.
[21] Parker SK. Beyond motivation: job and work design for development, health, ambidexterity, and more. Annu Rev Psychol 2014;65:661–91.
[22] Tennant G. Six Sigma: SPC and TQM in manufacturing and services. Aldershot, UK: Gower Publishing, Ltd; 2001.
[23] Snowder GD, Van Vleck LD, Cundiff LV, Bennett GL, Koohmaraie M, Dikeman ME. Bovine respiratory disease in feedlot cattle: phenotypic, environmental, and genetic correlations with growth, carcass, and longissimus muscle palatability traits. J Anim Sci 2007;85: 1885–92.
[24] Hodges RJ, Buzby JC, Bennett B. Postharvest losses and waste in developed and less developed countries: opportunities to improve resource use. J Agric Sci 2011;149(S1):37–45.
[25] Karnani A. Misfortune at the bottom of the pyramid. Greener Manag Int 2005;51:99–111.
[26] Brasch S. Milk vending machines take over Europe. Modern Farmer; 2014; March 25.
[27] Coghlan A. Africa's road to riches. New Sci 2014;221(2951):8.
[28] Ghiani G, Laporte G. Introduction to logistics systems management. Chichester, UK: John Wiley & Sons Ltd; 2013.
[29] Bar-Yosef B. Advances in fertigation. Adv Agron 1999;65:1–77.
[30] Barney JB. Firm resources and sustained competitive advantage. J Manag 1991;17(1):33–46.
[31] Barney JB, Clark DN. Resource-based theory: creating and sustaining competitive advantage. New York: Oxford University Press; 2007.
[32] Penrose ET. The theory of the growth of the firm. New York: Wiley; 1959.
[33] Spender JC. Making knowledge the basis of the dynamic theory of the firm. Strateg Manag J 1996;17(1):45–62.
[34] Coase R. The nature of the firm. Economica 1937;4(16):386–405.
[35] Williamson OE. The economics of organization: the transaction cost approach. Am J Sociol 1981;87(3):548–77.
[36] Madhok A. Reassessing the fundamentals and beyond: Ronald Coase, the transaction cost and the resource-based theories of the firm and the institutional structure of production. Strateg Manag J 2002;23(6):535–50.
[37] Poppo L, Zenger T. Testing alternative theories of the firm: transaction cost, knowledge-based, and measurement explanations for make-or-buy decisions in information services. Strateg Manag J 1998;19(9):853–77.
[38] Liao Y, Liao K, Hutchinson R. A conceptual framework for prototyping outsourcing in new product development: a knowledge-based view. J Manuf Technol Manag 2010;21(1):122–38.
[39] Nakamura K, Odagiri H. R&D boundaries of the firm: an estimation of the double-hurdle model on commissioned R&D, joint R&D, and licensing in Japan. Econ Innov New Technol 2005;14(7):583–615.
[40] Yang X, Ho E, Chang A. Integrating the resource-based view and transaction cost economics in immigrant business performance. Asia Pac J Manag 2012;29(3):753–72.
[41] Clinton HR. Bestshoring' beats outsourcing. Wall Str J, July 26.
[42] Sanusi L. Africa must get real about Chinese ties. Financial Times; 2013; March 11.
[43] Flynn D. Africa investment – China brings goods and roads, now Africa wants jobs. Reuters; 2013; July 21.
[44] Karnani A. Misfortune at the bottom of the pyramid. Greener Manag Int 2007;51:99–110.
[45] Baron A. Impoverished Haiti manufacturing its own Android tablet. Reuters; 2014; March 16.
[46] Ellram LM, Tate WL, Petersen KJ. Offshoring and reshoring: an update on the manufacturing location decision. J Supply Chain Manag 2013;49(2):14–22.
[47] Fratocchia L, Maurob C, Barbieric P, Nassimbenid G, Zanonie A. When manufacturing moves back: concepts and questions. J Purch Supply Manag 2014;20(1):54–9.
[48] Theyel G. Production location and sustainability. Int J Agile Syst Manag 2012;5(3):267–75.
[49] Bulow J. An economic theory of planned obsolescence. Q J Econ 1986;101(4):729–49.
[50] Cooper T. Inadequate life? evidence of consumer attitudes to product obsolescence. J Consum Policy 2004;27(4):421–49.
[51] Spiegelman H, Sheehan B. Getting rid of the throwaway society. Business 2006;28(2):1921.
[52] Buckley G, Henriques M, Salazar-Xirinachs JM. The promotion of sustainable enterprises, International Labour Organization. Geneva: International Labour Office; 2008.
[53] Dekel U, Brom S. Reconstruction for demilitarization. INSS Insight, No. 580. Tel Aviv, Isreal: The National Institute for Security Studies; 2014.
[54] Adekunle A. The nature of African boundaries. Afr Spectr 1983; 18(2):177–89. Institute of African Affairs at GIGA, Hamburg.
[55] Bogue R. Europe fights back with advanced manufacturing and assembly technologies. Assem Autom 2012;32(4):312–7.

[56] Fanga J, Huanga GQ, Li Z. Event-driven multi-agent ubiquitous manufacturing execution platform for shop floor work-in-progress management. Int J Prod Res 2013;51(4):1168–85.

[57] Friedrich K, Almajid A. Manufacturing aspects of advanced polymer composites for automotive applications. Appl Compos Mater 2013; 20(2):107–28.

[58] Tassey G. Competing in advanced manufacturing: the need for improved growth models and policies. J Econ Perspect 2014;28(1): 27–48.

[59] Vieira G, Varela MLR, Putnik GD. Technologies integration for distributed manufacturing scheduling in a virtual Enterprise. Commun Comput Inf Sci 2012;248:337–47.

[60] Valilai OF, Houshmand M. A collaborative and integrated platform to support distributed manufacturing system using a service-oriented approach based on cloud computing paradigm. Robot Comput – Integr Manuf 2013;29(1):110–27.

[61] Wittbrodta BT, Glovera AG, Lauretoa J, Anzaloneb GC, Oppligerc D, Irwind JL, et al. Life-cycle economic analysis of distributed manufacturing with open-source 3-D printers. Mechatronics 2013; 23(6):713–26.

[62] Pearce JM, Blair CM, Laciak KJ, Andrews R, Nosrat A, Zelenika-Zovko I. 3-D printing of open source appropriate technologies for self-directed sustainable development. J Sustain Dev 2010;3(4): 17–29.

[63] Waters R. Book review: the zero marginal cost society by Jeremy Rifkin. Financial Times; 2014; March 21.

PUBLICATION
IV

Expanding the scope of prosumption: a framework for analysing potential contri-butions from advances in materials technologies

Stephen Fox and Leijun Li

Technological Forecasting & Social Change, 79(4), 721-733.
https://doi.org/10.1016/j.techfore.2011.10.006

Technological Forecasting & Social Change 79 (2012) 721–733

Contents lists available at SciVerse ScienceDirect

Technological Forecasting & Social Change

Expanding the scope of prosumption: A framework for analysing potential contributions from advances in materials technologies

Stephen Fox *, Leijun Li

VTT Technical Research Centre of Finland, Vuorimiehentie 5, PL 1000, 02044 VTT, Espoo, Finland

ARTICLE INFO

Article history:
Received 7 July 2010
Received in revised form 26 September 2011
Accepted 10 October 2011
Available online 28 October 2011

Keywords:
Prosumption
Materials technologies
Analytical framework

ABSTRACT

A framework for analysing advances in materials technologies is introduced. This framework is used to underpin forecasting related to the expansion of prosumption. The term, prosumption, refers to the social change of individuals being directly involved in the design and production of the goods that they consume. It is explained why expanding the scope of this important social change depends much upon advances in materials technologies. The framework that is introduced addresses the limitations of extant methods. Firstly, the framework is oriented specifically to prosumption. It addresses fundamental factors that determine whether advances in materials technologies can better enable expansion of prosumption: chemical compositions, internal microstructures, shaping complexities, and surface characteristics. Secondly, application of the framework is not restricted to a particular type of materials technologies. Thirdly, its format is straightforward. The framework is explained through two cases of forecasting concerned with the expansion of prosumption. These forecasts were made in 2003, and were found to be accurate during subsequent years.

1. Introduction

Throughout human history, advances in materials technologies have made major contributions to social change. There were very significant changes in agricultural practices, production skills, and trading opportunities, for example, as materials technologies advanced through the Stone Age, the Bronze Age, and the Iron Age [1]. Accordingly, materials technologies are an established topic in the literature concerned with technological forecasting and social change [2–5]. Here, a framework for analysing advances in materials technologies is introduced. This framework is used to underpin forecasting related to the expansion of prosumption. The term, prosumption,[1] refers to the important social change of individuals being directly involved in the design and production of the goods that they consume [6,7]. In this paper, it is explained why expanding the scope of this major social change depends much upon advances in materials technologies. Political, economic, and social factors can also be important to expanding opportunities for prosumption. However, without advances in materials technologies the potential for expanding the scope of prosumption will be fundamentally restricted.

Since 2008, innovations have been introduced that enable customers/end-users to have authority over the design and production of their own original one-off goods. These prosumption offerings combine Web 2.0 with production technologies, such as additive manufacturing and composite forming, which depend upon advances in materials technologies. These prosumption offerings are being introduced by Web 2.0 start-up companies which are led by market-oriented entrepreneurs [8,9]. By contrast, many advances in materials technologies are achieved by materials scientists working in highly sophisticated laboratories which

---

* Corresponding author.
E-mail address: stephen.fox@vtt.fi (S. Fox).

[1] The term, prosumption, has more than one application. An alternative application is to describe the activities of particularly enthusiastic and knowledgeable consumers who seek to be to be professional in their consumption. They can do so by buying consumer goods, such as digital cameras with sophisticated features, which enable them to emulate the standards of professionals.

0040-1625/$ – see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.techfore.2011.10.006

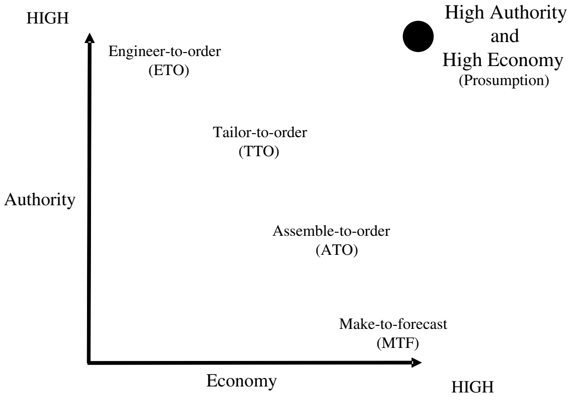


Fig. 1. High authority versus high economy.
Adapted from [31].

serve sectors such as such as global aerospace and off-world exploration [10–12]. Through its easy-to-follow structure for analysing advances in materials technologies, the framework that is introduced provides an accessible mean to underpin forecasting related to the expansion of prosumption. It can be useful for prosumption entrepreneurs as they seek to set up or expand start-up companies; for governments in post-industrial countries as they seek to determine how prosumption may address challenges such as revitalization of their manufacturing sectors; and for governments in Developing Countries as they seek to determine how prosumption could enable them to produce goods domestically without having to establish traditional industrial infrastructures [13].

The remainder of this paper comprises five principal sections. In the following section, the research methodology and research context are described. In section three, the framework is introduced and explained. In the fourth section, the use of the framework is illustrated through two cases of forecasting concerned with expanding the scope of prosumption. These forecasts were made in 2003, and have been found to be accurate during subsequent years. In the penultimate section, directions for future research are proposed. In the concluding section, the principal findings of the research are stated.

Overall, the contribution of this paper is to bring analysis of fundamental aspects of materials technologies into the scholarly literature addressing forecasting related to the important social change of prosumption.

2. Research methodology and research context

The findings reported in this paper emerged from action research, which was carried out in England and Finland between 1998 and 2010, among a variety of companies involved in the design and production of physical goods. Action research has its origins in the 1940s [14], and has increased in application throughout the subsequent decades [15]. Action research is used to influence or change some aspect of whatever is the focus of the research. The focus of the research was companies' operational strategies. The purpose of the action research was to influence companies' strategies to make them more robust in the face of increasing operational complexity due to increasing demands for individual customer authority and for lower delivery times and prices. Other findings from these action research interventions are reported elsewhere [16,17]. The analytical framework evolved through three stages as described in the following sub-sections.

2.1. Defining the authority versus economy trade-off[2]

A recurring feature of the action research interventions was the need to explain differences between offering individual customers choice through mass customization versus offering them authority over design and production. When the action research interventions began at the end of the 1990s there was considerable hype around the slogans “mass customization” and “customer as co-producers” [18,19]. During the subsequent 10 years, the hype surrounding these two slogans encouraged companies to adopt them. However, the vagueness of these two slogans led to companies being uncertain how to adopt them. The recurring need for explanation led to the formulation of a preliminary version of the diagram shown in Fig. 1. This diagram illustrates that offering both high authority and high economy at the same time necessitates going well beyond traditional industrial paradigms that operate at opposing positions in authority versus economy. Yet, this is what prosumption offerings need to achieve if they are to flourish in competition with offerings from traditional paradigms [6,7].

---

[2] This section, and this paper, addresses authority/economy trade-off from the perspective of the individual customer. This is different to the authority/economy trade-off perspective of companies as they seek to balance potential reduction of production authority against potential increase in production economy. That trade-off is addressed by Transaction Cost, Principal-Agent, and other theories that encompass the “make or buy” decision.

The companies involved in the action research operated within traditional paradigms that offer individual opportunities to have either determining inputs into the design and production of goods (i.e. authority) or offer them opportunities to have choices of goods with lower prices and shorter delivery times (i.e. economy). Fig. 1 illustrates that existing paradigms (ETO, TTO, ATO, MTF) do not offer both high authority and high economy. Rather, existing paradigms operate at opposing positions in the trade-off of: authority versus economy. Recognition of this trade-off was found to be implicit within descriptions of alternative paradigms within production literature. However, the authority versus economy trade-off was not explicitly represented in the prior literature [20–24].

Established paradigms that enable individuals to have determining inputs into design and/or production (ETO, TTO) result in individuals having original one-off goods. Goods are original and one-off when they originate in the mind of each individual customer and are made only once. It is important to note that original one-off goods are not goods that individuals configure from a range of pre-designed components. Nor are they pre-designed goods that individuals are only able to add graphical finishes to, such as personal emblems. In other words, original one-off goods are *not* goods that can be created with the types of mass customization configuration toolkits that became widespread during the period of the research [25,26]. Thus, offering individual customers more authority over design and production is fundamentally different from offering them more choices of product variants through mass customization.

Tailor-to-order processes offer individual customers authority over details of design and production. Engineer-to-order (ETO) processes offer individual customers authority over all of design and production. ETO processes employ engineering practices in the creation of goods such as ships and buildings. Small-scale ETO can include the creation of goods such as clothing and jewellery, and can be referred to as bespoke. Times and prices for ETO goods are generally much higher than for similar goods which are made-to-forecast (i.e. standard goods such as simple jewellery) or assembled-to-order (i.e. mass custom goods such as family cars). In other words, when individual customers are offered choice of standard or mass custom goods, they typically wait much less and pay much less compared to when they are offered authority over design and/or production. As illustrated in Fig. 1, in order for prosumption offerings to be successful they need to transcend the traditional authority versus economy trade-off between of established paradigms [6,7].

2.2. Prosumption forecasts based on analyses of materials technologies

Another recurring feature of the action research interventions was the need to explain the reasons for the fundamental trade-off summarized in Fig. 1. Reasons for the trade-off are rooted in materials properties. The body panels of mass custom cars, for example, need to be strong but, even though they are large, they also need to be light. Moreover, car body panels have geometries that are complicated in three dimensions. The properties of metals that can meet these performance requirements for car body panels necessitate the use of very large expensive product-specific production equipment, such as sets of large convex and concave moulds for shaping. Only these types of big capital investments can enable the accurate, consistent, quick and economical production of car body panels. However, for production to be economical there must be tens of thousands of vehicles sold to cover the costs of the capital investments in product-specific production equipment [27,28].

Unfortunately, it is neither technically feasible nor economically viable to develop product-specific production equipment for most original one-off customer-specific goods. It is not feasible because product forms cannot be pre-determined by manufacturers. Rather, manufacturers have to wait to find out what their next customer has in mind. It is not viable because when the customer-specific product forms have been defined, they are not repeated in the future. Thus, there is no possibility to recover the high investment costs of product-specific production equipment such as sets of large convex and concave moulds for shaping car body panels.

By contrast, there is not the same requirement for very expensive product-specific production equipment for components of smaller goods that do not have to be so strong and that do not have to have such complicated geometries. Examples of such components are clothing fabrics and watch casings. Rather, the materials properties needed to meet their performance requirements for strength, weight and geometry are compatible with much less expensive general-purpose production equipment. Indeed, advances in materials technology can make it possible for some minor prosumption without any production equipment. Consider, for example, the frames of spectacles that can be bent into the preferred fit shape by each individual wearer. These bendable eyeglasses are possible because of the sophisticated modification of the properties of selected metals [29].

Based on the factors summarized above, it was argued in 2003 that materials properties would not hinder future introduction of innovations that could enable individuals to have original one-off goods, such as clothes and jewellery with the same delivery times and prices as mass custom goods. Conversely, it was argued that materials properties would hinder future introduction of innovations that could enable individuals to have original one-off cars with the same delivery times and prices as mass custom goods [30]. The two arguments put forward in 2003, and summarized above, are stated below as propositions.

2003 Proposition 1. *The properties of materials used in mass custom goods such as clothes and jewellery will not hinder the introduction of prosumption innovations that can enable original one-off goods at mass custom times and costs.*

2003 Proposition 2. *The properties of materials used in mass custom cars will hinder the introduction of prosumption innovations that can enable original one-off cars at mass custom times and costs.*

Further, it was stated in 2003 that materials technologists would not be able to bring about sufficient modification of the metals used in mass custom cars to enable the prosumption of individual cars at mass custom times and costs [30]. Thus, tailoring the properties of car metals would not be sufficient to transcend the traditional trade-off between authority and economy. By contrast, it was argued in 2003 that making innovative combinations of craft practices and engineering processes has potential for transcending the traditional trade-off of authority versus economy [31]. Composite forming technology was put forward as an example of how innovative combinations of craft practices and engineering processes could reduce the times and costs of large individual goods. Typically, this involves manual skills in the laying and spraying of, for example, fibreglass cloth and thermosetting resin in the production of large panels with complicated geometries. The argument put forward in 2003, and summarized above, is stated below as a proposition.

2003 Proposition 3. *Innovative combinations of craft practices and engineering processes can transcend the traditional trade-off of authority versus economy for goods made from large complicated load-bearing components.*

The three forecasts, presented as propositions here, were made as the hype of terms, such as mass customization, suggested much: but clarified little for companies about what would, and would not, be possible for them in the foreseeable future.

2.3. Definition of formal analytical framework

From 2003, web-based mass customization tool kits became more sophisticated, but continued to provide individuals with little, if any, authority over the design and production of goods. Rather, brand holders enabled customers/end-users to participate in new product development through, for example, online communities and competitions. Subsequently after product launch, customers/end-users have been allowed to configure component options as they order the product online. Both component designs and allowable configuration options are determined in advance by companies — not by individual customers/end-users [32–35].

However, the coming emergence of web-based prosumption was well articulated in late 2006, when the CEO of Amazon, said: “Before long, ‘user-generated content’ won't refer only to media, but to just about anything. This is because setting up a company that designs, makes and globally sells physical products could become almost as easy as starting a blog — and the repercussions would be almost earthshaking” [36]. Subsequently, start-up companies began to introduce prosumption offerings that combine Web 2.0 with production technologies, such as additive manufacturing and composite forming [37,38].

The development of the formal analytical framework was initiated by the first author in 2010 when it became apparent that the forecasts he had made 7 years earlier were being proved to be accurate by the direction of prosumption offerings. Moreover, it was apparent that an easy-to-follow framework is needed to facilitate analyses of potential contributions to prosumption from materials that are developed in, for example, global aerospace and off-World exploration [10–12]. It was also apparent that an easy-to-follow framework is needed to facilitate analyses of potential contributions to prosumption from novel developments of indigenous materials. This is because prosumption has much potential to increase point-of-demand production, i.e. the production of physical goods much closer to where they are to be consumed.

Point-of-demand production can be more environmentally sustainable than the centralized production of traditional industrial paradigms. This is because centralized production involves massive fuel consumption and pollution emission because of transportation of materials and goods to and from factories. Within the development of off-World production solutions, the use of indigenous material (e.g. on the Moon) is referred to a in-situ resource utilization [39]. This concept is equally relevant to the development of “on-World” production solutions. For example, as more and more Developing Countries come online, there are more and more opportunities for prosumption start-ups to meet their needs for physical goods. This is not least because of absence of existing industrial infrastructure. Consider, for example, the 2009 statement of the president of Rwanda: In Africa, we have missed both the agricultural and industrial revolutions, and we are determined to take full advantage of the digital revolution [40]. The absence of existing industrial infrastructure enables Developing Countries to skip the unsustainable centralized industrial paradigms that have evolved in the Developed World since the Industrial Revolution. This is similar to Developing Countries going straight to mobile telecommunications and mobile banking; thus skipping over the fixed infrastructures that have evolved in the Developed World.

Reference to the literature revealed that existing methods, which involve analysis of advances in materials technologies, were not well-aligned to forecasting the expansion of prosumption. This is because they are either specific to one aspect of one type of materials technology [41,42] or they cover very general issues in the selection of materials technologies [43,44]. In either case, they do not address the fundamental factors which determine whether an advance in materials technology can enable expansion of prosumption. Further, many extant methods are very sophisticated and, as a result, not necessarily straightforward for people who are not materials experts to use.

The third stage of the research involved formalizing what had previously been the ad-hoc mental framework developed by the first author during action research interventions. The first two stages of the research did not involve the second author of this paper. The third stage of the research drew upon the second author's expertise as a scientist and teacher of materials technologies. The formal analytical framework is introduced in the next section.

3. Analytical framework

3.1. Purpose

The analytical framework addresses fundamental factors that determine whether advances in materials technologies can better enable the expansion of prosumption. Those fundamental factors are materials chemical compositions, internal microstructures, shaping complexities, and surface characteristics. The analytical framework facilitates comparison of established materials technologies with new materials technologies. Comparison is made in order to determine whether or not advances in materials technologies better meet a number of key criteria for expanding the scope of prosumption.

The analytical framework is intended to provide a sound technological basis for wider analyses that could encompass, for example, political, economic, and social factors. A sound technological basis is necessary to limit the hype that can often accompany the dissemination of technological innovation [45–48]. The prevalence of innovation hype is expressed in the titles of reports such as: What's Spurious, What's Real? [49]; The False Promise of Mass Customization [50], Nano-hype: The truth behind the nanotechnology buzz [51]. The analytical framework can be a useful starting point for prosumption entrepreneurs; for governments in post-industrial countries as they seek to determine how prosumption may address challenges such as revitalization of their manufacturing sectors [8]; and for governments in Developing Countries as they seek to determine how prosumption could enable them to produce goods domestically without having to establish traditional industrial infrastructures [13]. In order to encompass a broad range of potential users, the framework has a straightforward structure. The analytical framework is shown in Fig. 2, and described in the following sub-sections.

3.2. Materials' advantages and disadvantages for expansion of prosumption

Advantages for expanding prosumption are achieved when advances in materials technologies meet at least four key criteria. Firstly, production of original one-off goods must be facilitated. This can involve, for example, production of goods that have person-specific/location-specific geometries. Secondly, production of goods larger than those that can fit into a post box needs

Fundamental Factor	Existing Materials Technology	Relevant Advance in Materials Technology Advantages / Disadvantages for Expanding Prosumption		
		New Technology	Advantages	Disadvantages
Chemical composition				
Internal microstructures				
Shaping complexities				
Surface characteristics				

Fig. 2. Analytical framework.

to be local, i.e. at point-of-demand. Accordingly, many production facilities need to be much smaller than the massive factories of traditional centralized production. This can be achieved by, for example, housing production equipment within freight containers, which can be transported as necessary to points-of-demand [13]. Thirdly, production needs to be safe. Hence, human exposure to dangerous temperatures and equipment is not desirable. Fourthly, production needs to be fail-safe. Thus, the amount of specialist knowledge involved needs to less than that required for some traditional processes. These criteria arise from prosumption involving ordinary people at highly distributed locations producing what they consume.

Also, it is important to consider whether advances in materials technologies have disadvantages for the expansion of prosumption. Disadvantages include making person-specific, local, production more difficult. Disadvantages also include the introduction of greater production hazards and greater need for specialist knowledge. In addition, it is certainly a disadvantage if any advance in materials technology is less environmentally sustainable than existing alternatives.

3.2. Chemical compositions

Sometimes, the properties that are needed to fulfil performance requirements are inherent in materials. Many other times, the necessary properties have to be achieved through a variety of processes [52]. Materials technologies often improve chemical compositions through potentially dangerous processes. For example, stainless steels get their “stainlessness” when chromium is added to molten steel in a furnace at temperatures of approximately 1300 °C. Such processes are not well-suited to the expansion of prosumption. This is because they require very large facilities. Further, as much automation as possible is needed in these facilities to achieve competitive processing times and to minimise human risks from the dangerous temperatures involved. Specialized material-handling equipment and enclosed work zones are frequently employed [53]. Accordingly, many product manufacturers buy in the processed metals that they need. This often results in the long-distance physical transportation of heavy materials between countries and continents. This, in turn, leads to high fuel consumption and pollution emissions.

3.3. Internal microstructures

Similarly, materials technologies often improve internal microstructures through potentially dangerous processes. For example, rolling, forging and heat treatments of low alloy steel and aluminium alloy modify their internal microstructures so as to increase their strength [52]. Rolling is a forming process that involves bulky metal billets being flattened and thinned by the billets being squeezed through pairs of rollers. Forging refers to shaping of metal parts by large compressive forces. Heat treatment involves heating a shaped metal to a high temperature. Furnaces with large enough cavities to hold the steel components are required. Subsequent cooling is achieved in baths of brine, oil, or other cooling media. Both forging and heat treatments are carried out at very dangerous heats, which can rise up to 1000 °C.

Again, such processes are not well-suited to the expansion of prosumption, because they require very large facilities. Further, as much automation as possible is needed in these facilities to achieve competitive processing times and to minimise human risks from the dangerous temperatures involved. Specialized material-handling equipment and enclosed work zones are frequently employed [53]. Accordingly, many product manufacturers buy in the processed metals that they need. This often results in the long-distance physical transportation of heavy materials between countries and continents. This, in turn, leads to high fuel consumption and pollution emissions.

3.4. Shaping complexities

The potential of materials to be shaped into alternative geometric forms depends on complex interactions between characteristics such as their strength, toughness, and resistance to fatigue [54]. Often for smaller components, subtractive processes such as cutting and drilling are used to shape geometric forms from solid sections of materials. For larger components, forming moulds of several cubic meters in size may be used, together with huge hydraulic presses, or using very high pressure hydraulic fluid to press sheet metal into a large die [27,28].

Neither subtractive processes nor large-scale forming processes are well-suited to prosumption. In particular, subtractive processes would involve the transportation of solid material sections for point-of-demand prosumption. This involves the consumption of fuel and emission of pollution that adds no value, because much of what is transported is cut or drilled away into waste. Large-scale forming processes are not well-suited to the expansion of prosumption because they require very large facilities. Recovering the necessary investments depends upon tens of thousands of sales. In addition to the costs of factory buildings, production equipment costs are very high. For example, in order to cover the high overhead costs arising from investments in production equipment, it is necessary for car assembly factories to operate at about 80% of their capacity. This means that popular car types are often assembled and painted in advance. Then, they are placed in storage. This is necessary because there is not a continuous stream of customers throughout the year. Rather, there are peaks and troughs in annual demand. Subsequently, the pre-made cars are located at their storage place when a matching order is received from a customer, and then delivered. In other words, they are located-to-order after having been made-to-forecast. Thus, inventories of finished cars can be another source of high costs [50].

3.5. Surface characteristics

The surface characteristics of some materials reduce the amount of processing that they require. For example, the chemical compositions of stainless steels and titanium alloys provide them with anti-rust properties. However, stainless steels and titanium alloys are usually prohibitively expensive for goods that have large surface areas and complicated three dimensional geometries. Hence, they are used only for the bodies of big budget special vehicles that must meet exceptionally challenging performance requirements. Examples include the SR-71 Blackbird Reconnaissance Stealth Plane and the Mars Exploration Rover robotic vehicles [55,56].

By contrast, elaborate surface treatment processes, such as anodizing, galvanizing and painting, are often needed to give required surface properties to less expensive materials [57]. These processes may not be well-suited to prosumption because they are potentially dangerous and can be expensive. For example, anodizing is an electrolytic passivation process used to increase the thickness of the natural oxide layer on the surface of metal parts. The process is called “anodizing” because the metal to be treated forms the anode electrode of an electrical circuit. Galvanizing refers coating the steel parts with zinc, usually in a bath that contains molten zinc metal [58].

4. Applying the analytical framework

In this section, two examples of prosumption innovation are analysed using the formal framework. The two examples are watch casings and car body panels. There has been interest in involving customers in the development phase, and/or configuration of watches and of cars for some years [25,59]. The example of watch casings is used here because it is a type of component that has relatively high materials performance requirements compared to many other types of components used in smaller goods such as clothes and jewellery. Further, watch casings, like car body panels, can be made of metals which have improved properties through modification processes.

4.1. Application case 1: watch casings

As argued in 2003, Proposition 1 is that the properties of materials used in some mass custom goods, such as clothes and jewellery, will not hinder the introduction of prosumption innovations that enable original one-off goods at mass custom times and costs. Since 2003, mass customization tool kits for clothes and watches may have become more refined. However, they continue to limit individuals' participation to the selection and configuration of pre-designed components (e.g. www.blank-label.com; www.blancier.com). In addition, there have been prosumption innovations introduced since 2003 that do enable individuals from outside traditional value chains for design and production to create their own original one-off goods [8,9].

These prosumption innovations make use of additive manufacturing technologies (AM) such as 3D printing. 3D printing involves creating a three dimensional object from a digital CAD (computer-aided design) file by placing successive layers of material on top of each other to build a physical object. Hence, 3D printers are sometimes referred to as Object Printers. This direct placement of material eliminates the need for moulds and presses. In common with other types of AM, 3D printing places material only exactly where it is needed to produce a robust component or product. This eliminates the need for subtractive processes such as cutting metals to shape on a lathe. Overall, AM can radically reduce the amount of material needed to manufacture a component. Moreover, AM can enable far greater geometric freedom than could be achieved traditionally with lathes or moulds [60].

With regard to additive manufacturing of metal watch casings, recent advances in a technology called Direct Metal Laser-Sintering (DMLS) enables the very efficient use of stainless steels and titanium alloys in unique geometrical forms. DMLS fuses metal powder into a solid part by melting it locally using the focused laser beam. Components are built up additively layer by layer, typically in increments of 20 μm. DMLS produces components with thermal, chemical, mechanical and geometric properties that are comparable with those of components produced conventionally [61].

Overall, it can be argued that the properties of materials used in mass custom watch casing have done little to hinder the introduction of prosumption innovations for original one-off watch casings. In particular, stainless steels and titanium alloys are used in mass custom production and in DLMS production. With regard to production times and costs, the efficiency of additive manufacturing is continually being improved through both technology-push and market-pull. This is leading to the increasing proliferation of AM service bureaus that carry out production on demand for individual customers. Accordingly, individuals who wish to create their own piece of original one-off jewellery do not have to make any capital investments in buildings, equipment and/or inventories. Further, the increasing robustness of digital data transfer via the Internet makes it increasingly possible for individuals anywhere in the world to participate [62]. A summary of the advantages and disadvantage of Direct Metal Laser-Sintering (DMLS) is provided in the new analytical framework, shown as Fig. 3.

With regard to chemical composition, the metal alloys used in DMLS are similar to the metal alloys traditionally used for watch casings. Accordingly, large-scale alloying processes are required to produce the metals used in DMLS. Thus, there are neither advantages nor disadvantages. With regard to internal microstructures, rolling and forging are not required for the metal alloys used in DMLS. However, they do have to be atomized to produce the necessary metal alloy powders. Hence, advantages are cancelled out by disadvantages. With regard to shaping complexities, DMLS offers more geometric freedom than traditional production processes, and make the manufacture of unique geometries less complex for prosumers. Accordingly, DMLS offers a clear advantage. With regard to surface characteristics, DMLS components produced with stainless steels or titanium alloys may require some grinding and polishing, depending on the finest of metal powders used. Thus, DMLS does not offer a notable advantage.

Fundamental Factor	Existing Materials Technology	Relevant Advance in Materials Technology Advantages / Disadvantages for Expanding Prosumption		
		New Technology	Advantages	Disadvantages
Chemical composition	Alloying titanium with small amounts e.g. Vanadium produces titanium alloy that meets chemical and thermal performance requirements	Large-scale alloying processes still required	No advantage	No disadvantage
Internal microstructures	Rolling and forging titanium alloy produces high strength titanium alloy that meets mechanical performance requirements	Metals have to be melted and atomized to produce powders for DMLS	Rolling and forging not required	Atomizing required
Shaping complexities	Small scale 2D subtractive processes such as turning, drilling, polishing produces high strength stainless steel / high strength titanium that meet geometric performance requirements	Additive manufacturing	Greater variety of near net shapes can be achieved with less prior knowledge, and without moulds and presses, or small scale subtractive processes	No disadvantage
Surface characteristics	No additional processes necessary	No additional processes necessary	No advantages	Dependent on fineness of powder to achieve a smooth surface finish

Fig. 3. Application case 1: DMLS for watch casings.

Overall, it can be argued that DMLS does reduce the traditional trade-off between authority and economy. Indeed, it could be argued that DMLS is close to transcending the traditional trade-off between authority and economy. This is because DMLS allows individuals to express their own individual geometric creativity at times and costs that are approaching those for mass custom goods. Neither product-specific moulds, nor the skill of metal turning on a lathe, are required. Moreover, DMLS can produce very complicated geometric forms as one single piece. By contrast, two or more components may have to be made separately, and then joined together, when moulds or lathes are used. DMLS has been made possible through materials technologies innovations in metal powders.

In particular, DMLS makes contributions to meeting key criteria for expanding the scope of prosumption, because it better enables safe and simple production of person-specific/location-specific geometries.

4.2. Application case 2: car body panels

It was argued in 2003, and stated in Proposition 2 above, that the properties of materials used in mass custom cars do hinder the introduction of prosumption innovations for original one-off car body panels. For example, additive manufacturing with metals is not applicable to the production of car body panels. This is because the AM technologies for metals are thus far limited to desk-top size components. One reason for this is that in laser-based processes, such as DLMS, heating to very high melting temperatures is needed for the component to take the shape. Subsequently, major shrinkage and thermal stresses are generated during cooling. This can lead to porosity, cracking, and inappropriate internal microstructures. Hence, very precise control is needed during cooling in order to achieve appropriate mechanical properties. The necessary precision of control is feasible and viable for components the size of a watch casing, but not for components the size of car body panels.

Much larger sized additive manufacturing has been introduced for building components. However, large building components have very different performance requirements compared to car body panels. Both have to have good mechanical performance, but car body panels also have to be light in weight. Typically, additive manufacturing creates large building components by combining a binder material, such as an adhesive polymer, with a particulate material, such as sand. The resultant strength of the component is limited by the strength of the binder and how strong the particles are "glued" by the binder. Moreover, the time required to form large building components is very much longer than the few seconds required to form a car body panel using large moulds and presses. In addition, the initial investment in large additive manufacturing equipment for large building components is very costly [63].

More broadly, it can be argued that there have been few, if any, notable advances in metals technologies relevant to car body panels since 2003. There may be several factors contributing to this lack of advancement. In particular, metals involved in making car body panels had already been refined over more than 50 years of incremental innovation. Accordingly, it could be considered that there are few, if any, major gains to be made from substantial investment in further innovation. Also, much of the focus of materials innovation is now concerned with nanotechnologies, and their potential to enable new vehicle attributes such as scratch-resistant car paint, dirt resistant car windows etc. [64]. In addition, mass custom car makers have been occupied by expanding existing brands into emerging mass markets such as China and India [65]. This involves expansion of established paradigms for production, and does not depend on innovations in materials technologies. Accordingly, since 2003, mass customization tool kits for cars have become more refined, but continue to limit individuals' participation to the selection and configuration of pre-designed components for pre-designed vehicle types (e.g. www.citroen.co.uk/new-cars/car-configurator/; www.volvocars.com/uk/sales-services/sales/pages/car-configurator.aspx).

Interestingly, a car prosumption company started in 2009 makes use of composites, rather than metal, for body panels. The example of composites was given in 2003 to illustrate how craft practices and engineering processes can be combined in efforts to transcend the traditional trade-off of authority versus economy [31]. The new company offers much greater participation by individuals that are outside of traditional value chains for design and production. Although the company does not offer original one-off cars at mass custom times and prices, it is feasible and viable for the company to offer as few as five hundred of each type of original car. The cars are competitively priced street legal off-road vehicles. By its use of composite body panels, rather than metal body panels the company avoids the types of major overhead costs outlined above in section 3. Those are huge buildings; large moulds and presses; and inventories of finished goods. This enables it to reduce the break-even point for production from tens of thousands of cars to hundreds of cars [66].

Compared to metals technologies relevant to car body panels, there is much more innovation in composite technologies. For example, Virtual Engineered Composites (VEC) can combine several different thermoplastic polymers with their own particular properties. These can include a clear, outer acrylic layer that provides chemical and scratch resistance, gloss, and depth of image. Then, a second layer can provide the required colour, and resistance to ultra-violet light. Next, a third layer can provide strength sufficient to maintain structural integrity until the geometric form can be bonded to the fibreglass composite itself (www.vectechnology.com/vec-system.cfm). A summary of the advantages and disadvantage of Virtual Engineered Composites (VEC) is provided in the new analytical framework, shown as Fig. 4.

With regard to chemical composition, metals are not used in VEC. Accordingly, large-scale metal alloying processes are not required. On the other hand, the processes needed to produce fibreglass, resins and plastics also require large-scale capital investments in big buildings and processing equipment. Moreover, a greater diversity of processes is required to produce the greater diversity of material involved. Hence, the advantages are cancelled out by the disadvantages.

With regard to internal microstructures, rolling, forging and heat treating are not required for VEC. However, achieving the correct internal microstructures can be more challenging for composite panels than for sheet metal. This is because composites comprise several materials rather than just one. Moreover, the different materials have different properties. Conventional thermoplastic polymers, for example, can become brittle in cold weather or can become soft and warp in hot weather. Accordingly, different thermoplastic polymers are developed with modified properties to suit the performance requirements of different products. Heavy-duty composites, for example, can use thermosetting polymers that are less vulnerable to heat, and have better mechanical properties. However, they are more difficult to mould into a large shape that is complicated in three-dimensions.

With regard to shaping complexities, VEC offers equal geometric freedom to traditional production processes, but without the need for such heavy industrial equipment. Accordingly, VEC offers clear advantages. With regard to surface characteristics, VEC offers the important advantages of eliminating the need for galvanizing and painting. This is because weather protection and colour are manufactured into the VEC panels through the combination of appropriate plastics. There is, however, potential for increased risk of ultraviolet radiation (UV) damage.

Overall, it can be argued that VEC has reduced the traditional trade-off between authority and economy, because it has eliminated the need for huge hydraulic presses, sets of steel moulds etc. As a result, VEC better enables distributed production that is closer to points-of-demand. Nonetheless, VEC is not a viable alternative for the production of an original one-off. Rather, there are still substantial mould-making costs that have to be recovered. VEC moulds are themselves composites comprising materials such as polyurethane foam, fibreglass, and polyester-based primer. However, instead of using thick metal sections to set up a rigid hydraulic system for pressing VEC moulds together, a non-compressible fluid (e.g. water) is used to support the mould shells. Thus, VEC involves significant materials innovation for production equipment, as well as for product components.

Fundamental Factor	Existing Materials Technology	Relevant Advance in Materials Technology Advantages / Disadvantages for Expanding Prosumption		
		New Technology	Advantages	Disadvantages
Chemical composition	Alloying steel with very small amounts of e.g., Chromium, produces low alloy steel that meets thermal performance requirements	Manufacture of composite sheets	Large scale metal alloying processes are not required	Production of fibre cloths, resins, plastics sheets are required
Internal microstructures	Rolling, forging, and heat treating low alloy steel produces high strength steel that meets mechanical performance requirements	Bonding and pressing together of composite sheets between moulds	Rolling, forging, and heat treating not required	Dependence on integrity of bonding between different materials
Shaping complexities	Large scale 3D subtractive, forming, and joining processes such as stamping, bending, pressing, hydroforming, cutting, drilling, welding produces high strength steel / high strength aluminium that meets geometric performance requirements		Lighter, cheaper moulds that can be produced without needing dangerous temperatures, huge buildings and large hydraulic presses, hence can be carried out closer to point-of-demand	Dependence on less mature processes
Surface characteristics	Galvanizing and painting high strength steel produces anti-rust high strength steel that meets chemical performance requirements	No additional processes required	Neither galvanizing and painting, nor anodizing or painting are required	Increased risk of UV damage

Fig. 4. Application case 2: car body panels.

5. Directions for future research

In this section it is argued that introduction of the new analytical framework can make a contribution to two directions for future research. Firstly, the comparative analysis of new materials technologies against existing materials technologies can support identification of fundamental factors in need of further improvement. Secondly, comparative analysis of materials technologies can support identification of broader prosumption issues, which may need to be addressed.

5.1. Materials technologies research to expand prosumption

Comparative analyses with the formal framework can support identification of the limitations of new materials technologies, and so support identification of directions for further research and development. Consider, for example, the case of VEC. It has eliminated the need for huge hydraulic presses, sets of steel moulds etc., and so better enables point-of-demand production. However, it is not a viable alternative for the production of an original one-off. Moreover, any production process that involves product-specific sets of concave and convex moulds is likely to remain too expensive for original one-off goods with large complicated three-dimensional geometries. This is because of the need for the high accuracy of conformance between the two moulds, and the extreme forces involved in pressing them together.

However, these two fundamental sources of costs in production processes are not present in traditional composite manufacturing. This is because only a single bottom mould is required, together with the laying and spraying of, for example, fibreglass cloth and thermosetting resin onto the top of the mould. Subsequently, the composite panel is removed and painted. Accordingly, to additional propositions for further research and development work can be put forward.

Proposition 4. *Advances in materials technologies focused on producing single moulds will further reduce the times and costs of producing large complicated load-bearing composite components for original one-off goods.*

Proposition 5. *Advances in materials technologies focused on lowering dependency on craft skills will further reduce the times and costs of producing large complicated composite load-bearing components for original one-off goods.*

Advances in materials technologies focused on producing single moulds could, for example, involve developing innovative types of light-weight solid foam materials that can be easily and accurately shaped into the required mould geometries. This could be achieved by, for example, using computer controlled foam cutting equipment that is driven directly from a CAD file. Advances in materials technologies focused on lowering dependency on craft skills could, for example, involve improving the filling properties of primers used to coat composite panels before painting. It is important to note that there is far more on-going materials innovation in composites panels than in sheet metals used for mass custom car bodies. In the aircraft industry, for example, improved composites are being developed and deployed. This is because of their better strength to weight ratio than metal alternatives. This, in turn, enables significant reductions in aircraft weight and, thus, aircraft fuel consumption [67].

5.2. Holistic research to expand prosumption

Advances in materials technologies are necessary to enable the expansion of prosumption, but often they may not be sufficient to enable the expansion of prosumption. Political, economic, and social issues also have to be taken into consideration. Product liability, for example, can be an important issue for goods, such as automotive vehicles, which can affect public safety. Broader analyses could consider the political, economic, and social consequences of product liability becoming distributed among many prosumers, rather than centralized among a few brand holders. Simultaneously, it is necessary to determine how political, economic, and social factors could be structured to enable product liability to be responsibly distributed among many prosumers. This could be particular challenging when goods, such as automotive vehicles, produced by prosumers travel between countries and to different parts of the world.

Broad research of factors related to the expansion of prosumption would need to encompass local issues, as well as global factors. For example, there are many political, economic, and social differences between governments in post-industrial countries that seek to “rebalance” their economies [68]; and governments in Developing Countries as they seek to determine how to produce goods domestically without having to establish traditional industrial infrastructures [69]. Accordingly, it is unlikely that political, economic, and social measures that facilitate the expansion of prosumption at one place would be effective at another [70]. For example, point-of-demand prosumption may be politically, economically, and socially welcome in land-locked Developing Countries, such as Burundi, where the as much as 75% of the price of many physical goods can be due to transportation costs. By contrast, point-of-demand prosumption may be less welcome in post-industrial countries where traditional industrial incumbents have political influence and transportation costs are much lower.

In addition to high level political, economic, and social factors, holistic prosumption research can encompass implementation issues such as motivation and communication [71,72]. Holistic research can yield essential information for use in the application of forecasting methods and tools, such as scenario planning, roadmapping, Dephi, etc. [73,74].

6. Conclusions

An analytical framework has been introduced which can be used to explore the fundamentals of materials properties, and how they can be improved through advances in materials technologies. Through application of the analytical framework, the validity of three propositions about the expansion of prosumption has been assessed. Assessment offers initial support for the propositions, which were first put forward during 2003. In particular, the properties of metals used in mass custom jewellery, such as watches, have not hindered the introduction of prosumption innovations that can enable individual goods at mass custom times and costs. By contrast, it can be argued that the properties of metals used in mass custom cars can hinder the introduction of prosumption innovations that enable original one-off cars at mass custom times and costs. Instead of these metals, composite materials are being used. Composite materials are an example of innovative combinations of craft practices and engineering processes. It was this combination that was put forward in 2003 as having potential to transcend the traditional authority versus economy trade-off for goods made from large complicated load-bearing components.

In addition, two directions for further research have been proposed. Firstly, it has been proposed that materials technologies research to expand prosumption can be informed by application of the new framework. Two examples have been introduced: advances in materials technologies focused on reducing the times and costs of engineering practices; and advances in materials technologies focused on reducing dependency on craft skills. The second direction proposed for future research is holistic studies that encompass political, economic, and social factors. This is because, while advances in materials technologies are necessary to enable the expansion of prosumption, often they may not be sufficient to enable the expansion of prosumption.

Overall, this paper makes a new contribution to technological forecasting literature. In particular, an analytical framework has been introduced which can be used to explore the fundamentals of materials properties, and how they can be improved through technological advances. Most importantly, the analytical framework can provide a means for identifying those advances in materials technologies with most potential to contribute to the important social change of prosumption. This is essential to address the inflated claims made for some advances in materials technologies, and to determine which advances in materials technologies should be prioritized for exploitation through knowledge infrastructures, innovation systems etc.

References

[1] R.E. Hummel, Understanding Materials Science, Springer-Verlag, New York, 2004.

[2] J. Van den Ende, K. Mulder, M. Knot, E. Moors, P. Vergragt, Traditional and modern technology assessment: toward a toolkit, Technol. Forecast. Soc. Chang. 58 (1–2) (1998) 5–21.

[3] R.J. Watts, A.L. Porter, Innovation forecasting, Technol. Forecast. Soc. Chang. 56 (1) (1997) 25–47.

[4] I.K. Wernick, Consuming materials: the American way, Technol. Forecast. Soc. Chang. 53 (1) (1996) 111–122.

[5] E. Williams, Forecasting material and economic flows in the global production chain for silicon, Technol. Forecast. Soc. Chang. 70 (4) (2003) 341–357.

[6] A. Toffler, The Third Wave, Bantam Books, New York, 1980.

[7] G. Ritzer, N. Jurgenson, Production, consumption, prosumption, J. Consum. Cult. 10 (1) (2010) 13–36.

[8] S. Fox, Manufacturing goes online as Factory 2.0, Eng. Technol. 4 (15) (2009) 62–63.

[9] S. Fox, Made-to-measure: web 2.0 with digital tools for design and production, Project (2010) 12–14 February.

[10] G. Marsh, Airbus takes on Boeing with reinforced plastic, Reinf. Plast. (2007) 26–28 December.

[11] W.P. Schonberg, Protecting Earth-orbiting spacecraft against micro-meteroid/orbital debris impact damage using composite structural systems and materials: an overview, Adv. Space Res. 45 (2010) 709–720.

[12] I. Kondyurina, A. Kondyurin, B. Lauke, L. Figiel, R. Vogel, U. Reuter, Polymerisation of composite materials in a space environment for development of a Moon base, Adv. Space Res. 37 (2006) 109–115.

[13] S. Fox, After the factory: renewing industry without going off-shore, Eng. Technol. 5 (8) (2010) 59–61.

[14] K. Lewin, Action research and minority problems, J. Soc. Issues 2 (1946) 34–36.

[15] E.T. Stringer, Action Research, 2 ed., Sage Publications, Thousand Oaks, CA, USA, 1999.

[16] S. Fox, T. Jokinen, N. Lindfors, J.-P. Ylen, Formulation of robust strategies for project manufacturing business, Int. J. Manag Projects Bus. 2 (2) (2009) 217–237.

[17] S. Fox, G. Cockerham, I. Staniforth, Bespoke as standard, Manuf. Eng. 80 (3) (2001) 139–142.

[18] C. Huffman, B.E. Kahn, Variety for sale: mass customization or mass confusion, J. Retail. 47 (4) (1998) 491–513.

[19] S. Wikstrom, The customer as co-producer, Eur. J. Mark. 30 (4) (1996) 6–13.

[20] J. Dilworth, Production and Operations Management, McGraw-Hill, Singapore, 1989.

[21] R. Handfield, Distinguishing features of just-in-time systems in the make-to-order/assemble-to-order environment, Decis. Sci. 24 (3) (1993) 581–602.

[22] T. Hill, Manufacturing Strategy: The Strategic Management of the Manufacturing Function, The Macmillan Press, New York, 1993.

[23] R. Schroeder, Operations Management: Decision Making in the Operations Function, McGraw-Hill Inc., New York, 1993.

[24] J. Wortmann, Production management systems for one-of-a-kind products, Comput. Ind. 19 (1) (1992) 79–88.

[25] N. Franke, P. Keinz, M. Schreier, Complementing mass customization toolkits with user communities: how peer input improves customer self-design, J. Prod. Innovations Manage. 25 (6) (2008) 546–559.

[26] T. Randall, C. Terwiesch, K.T. Ulrich, User design of customized products, Market. Sci. 26 (2) (2007) 268–280.

[27] M.A. Vonderembse, G.P. White, Operations Management: Concepts, Methods, and Strategies, Wiley, Danvers, MA, 2004.

[28] D. Welch, Can Stodgy GM Turn Stylish, Business Week, 2002 11 November.

[29] M.J. Donachie Jr., Titanium, A Technical Guide, 2nd ed. ASM International, Cleveland, OH, 2000.

[30] S. Fox, Recognizing materials power, Manuf. Eng. 81 (3) (2003) 36–39.

[31] S. Fox, Technology splicing, Manuf. Eng. 81 (6) (2003) 24–27.

[32] V. Bilgram, A. Brem, K.-I. Voigt, User-centric innovations in new product development — systematic identification of lead users harnessing interactive and collaborative online-tools, Int. J. Innov. Manag. 12 (3) (2008) 419–458.

[33] B.G.C. Dellaert, S. Stremersch, Marketing mass-customized products: striking a balance between utility and complexity, J. Market. Res. 42 (2) (2005) 219–227.

[34] J. Füller, K. Matzler, Virtual product experience and customer participation — a chance for customer-centred really new products, Technovation 27 (6–7) (2007) 378–387.

[35] C.K. Prahalad, V. Ramaswamy, The Future of Competition: Co-creating Unique Value with Customers, Business School Press, Boston, MA, Harvard, 2004.

[36] K. Maney, Amazon's New Direction: Point, Click, Make a Product to Sell to the World, USA Today, 2006 21st November.

[37] C. Anderson, In the next industrial revolution, atoms are the new bits, Wired (2010) 18th February, 58–62.

[38] C. Anderson, How to make stuff, Wired (2011) 19th April, 90–113.

[39] K.L. Murphy, V.Ye Rygalov, S.B. Johnson, Minimal support technology and in situ resource utilization for risk management of planetary spaceflight missions, Adv. Space Res. 43 (2009) 1275–1284.

[40] E. Kircher-Allen, Rwanda bids to become East Africa's WiFi hotspot, Global Post, 2009 30th December.

[41] S. Ghosh, Adaptive concurrent multi-level model for multi-scale analysis of composite materials including damage, in: Y. Kwon, D.H. Allen, R. Talreja (Eds.), Multiscale Modeling and Simulation of Composite Materials and Structures, Springer, 2008, pp. 83–164.

[42] I.A. Roberts, C.J. Wang, R. Esterlein, M. Stanford, D.J. Mynors, A three-dimensional finite element analysis of the temperature field during laser melting of metal powders in additive layer manufacturing, Int. J. Mach. Tools Manuf. 49 (12–13) (2009) 916–923.

[43] E. Maine, D. Probert, M. Ashby, Investing in new materials: a tool for technology managers, Technovation 25 (1) (2005) 15–23.

[44] W. Bolton, M. Philip, Technology of Engineering Materials, Butterworth-Heinemann, Oxford, UK, 2002.

[45] J. Fenn, M. Raskino, B. Gammage, Gartner's Hype Cycle Special Report for 2009, Gartner, Stamford, CT, 2009.

[46] M. Lord, D. deBethizy, J. Wager, Innovation that fits: moving beyond the fads to choose the right innovation strategy for your business, Pearson Prentice Hall, Upper Saddle River, NY, 2005.

[47] P. Wang, Chasing the hottest IT: effects of information technology fashion on organizations, MIS Q. 34 (1) (2010) 63–85.

[48] G. Tichy, The over-optimism among experts in assessment and foresight, Technol. Forecast. Soc. Chang. 71 (4) (2004) 341–363.

[49] T. Hempell, What's spurious, what's real? Measuring the productivity impacts of ICT at the firm-level, Centre for European Economic Research, Mannheim, 2002.

[50] M. Agrawal, T.V. Kumaresh, G.A. Mercer, The false promise of mass customization, McKinsey Q. 38 (3) (2002) 62–71.

[51] D.M. Berube, Nano-hype: The Truth Behind the Nano-Technology Buzz, Prometheus Books, Amherst, NY, 2006.

[52] S. Kalpakjian, S.R. Schmid, C.-W. Kok, Manufacturing Processes for Engineering Materials, 5th ed. Pearson, Upper Saddle River, NJ, 2007.

[53] S. Kreipl, M. Pinedo, Planning and scheduling in supply chains: an overview of issues in practice, Prod. Oper. Manage. 13 (1) (2004) 77–92.

[54] R.E. Smallman, A.H.W. Ngan, Physical Metallurgy and Advanced Materials, 7th ed. Butterworth-Heinenman, Oxford, 2007.

[55] M. Burgan, The World's Fastest Military Airplanes, Capstone Press, Mankato, MN, 2001.

[56] J.K. Erickson, M. Adler, J. Crisp, A. Mishkin, R. Welch, Mars exploration rover: surface operations, 53 rd International Astronautical Congress, Houston TX, USA, October 10–17, 2002.
[57] P.G. Sheasby, R. Pinner, The Surface Treatment and Finishing Of Aluminium and Its Alloys, ASM International, Cleveland, OH, 2001.
[58] D. Taylor, Paint & Body Handbook, HP Trade, New York, 1994.
[59] N. Franke, F. Piller, Value creation by toolkits for user innovation and design: the case of the watch market, J. Prod. Innov. Manag. 21 (6) (2004) 401–415.
[60] N. Hopkinson, R. Hague, P. Dickens, Rapid manufacturing: an industrial revolution for a digital age, Wiley, Chichester, UK, 2005.
[61] L.S. Bertol, W. Kindlein, F.P. da Silva, C. Aumund-Kopp, Medical design: direct metal laser sintering of Ti-6Al-4 V, Mater. Des. 31 (8) (2010) 3982–3988.
[62] H. Lan, Web-based rapid prototyping and manufacturing systems: a review, Comput. Ind. 60 (9) (2009) 643–656.
[63] Z. Yeh, B. Khoshnevis, Geometric conformity analysis for automated fabrication processes generating ruled surfaces: demonstration for contour crafting, Rapid Prototyping J. 15 (5) (2009) 361–369.
[64] V.S. Saji, J. Thomas, Nanomaterials for corrosion control, Curr. Sci. 92 (1) (2007) 51–55.
[65] M. Chamon, P. Mauro, Y. Okawa, Mass car ownership in the emerging market giants, Econ. Policy 23 (54) (2008) 243–296.
[66] C. Anderson, In the next industrial revolution, atoms are the new bits, Wired, 2010 January 25.
[67] S. Kristoff, The Boeing 787 dreamliner: the first majority-composite commercial aircraft, Mech. Eng. (2009) suite101, December 15.
[68] The economist, less paper, more iron: politicians want to boost British manufacturing. Easier said than done, The Economist, London, 2011 July 7.
[69] M. Nkwame, High Transport Cost Impedes Trade at EA, Tanzania Daily News, Dar es Salaam, 2011, February 28.
[70] J.G. Koomey, Avoiding "The Big Mistake" in forecasting technology adoption, Technol. Forecast. Soc. Chang. 69 (4) (2004) 511–518.
[71] C. Droge, M.A. Stanko, W.A. Politte, Lead users and early adopters on the web: the role of new technology product blogs, J. Prod. Innov. Manag. 27 (1) (2009) 66–82.
[72] S. Nambisan, R.A. Baron, Virtual customer environments: testing a model of voluntary participation in value co-creation activities, J. Prod. Innov. Manag. 26 (4) (2009) 388–406.
[73] V. Coates, M. Farooque, R. Klavans, K. Lapid, H.A. Linstone, C. Pistorius, A.L. Porter, On the future of technological forecasting, Technol. Forecast. Soc. Chang. 67 (1) (2001) 1–17.
[74] R. Phaal, C.J.P. Farrukh, D.R. Probert, Technology roadmapping — a planning framework for evolution and revolution, Technol. Forecast. Soc. Chang. 71 (1–2) (2004) 5–26.

Stephen Fox PhD is a Senior Research Scientist at VTT Technical Research Centre of Finland. His research and development work is focused on technology evaluation, synthesis, and implementation. He has published papers in Critical Perspectives on Accounting, Journal of Manufacturing Technology Management, and other journals.

Leijun Li PhD is an Associate Professor at Utah State University. His research interests include processing, testing, and characterization of materials and structures; underlying process physics, microstructures, and mechanical properties. He has published papers in Journal of Advanced Materials, Journal of Engineering Manufacture, and other journals.

PUBLICATION
V

A taxonomy of manufacturing distributions and their comparative relations to sustainability

Stephen Fox and Büşra Alptekin

Journal of Cleaner Production, 172: 1823-1834.
https://doi.org/10.1016/j.jclepro.2017.12.004

Journal of Cleaner Production 172 (2018) 1823–1834

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A taxonomy of manufacturing distributions and their comparative relations to sustainability

Stephen Fox*, Büşra Alptekin

VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT, Finland

ARTICLE INFO

Article history:
Available online 5 December 2017

Keywords:
Artisanal distributed manufacturing
DIY distributed manufacturing
Industrial distributed manufacturing
Centralized manufacturing
Sustainable production
Taxonomy
Turkey

ABSTRACT

There are many different types of manufacturing distributions, ranging from subsistence do-it-yourself (DIY) to centralized industrial production. In this paper, a taxonomy is introduced of alternative manufacturing distributions for sustainable production. First, different types of manufacturing distributions are explained. Second, the importance of location-specific considerations is illustrated through a case study of Turkish car production. Third, comparative sustainability analysis for different manufacturing distributions is provided. This includes economic, ecological, social and institutional sustainability. Fourth, factors affecting the sustainability of all manufacturing distributions are explained. Fifth, the taxonomy is introduced, together with an example of comparative sustainability analysis for two alternative types of manufacturing distributions. Overall, it is argued that different manufacturing distributions have different strengths and weaknesses depending on multiple factors. Moreover, in some situations, centralized manufacturing can have higher potential for sustainable production than other distributions of manufacturing. Hence, the taxonomy is introduced to facilitate increased specificity and balance in debate concerning alternative manufacturing distributions for sustainable production.

1. Introduction

It has been claimed that distributed manufacturing can improve the sustainability of production (Kohtala, 2015; Rauch et al., 2016). However like many adjectives, distributed is a vague word with indeterminate boundaries (Sorensen, 2006). Hence, there are many different distributions of manufacturing that could be considered to distributed manufacturing.

For example, do-it-yourself (DIY) manufacturing is distributed in households around the world (FEDIYMA, 2016). Also, artisanal manufacturing is distributed around the world at rural and urban locations (Ardalan, 2017). In addition, industrial manufacturing is distributed internationally at producers of parts (Carbone, 2000) and products (Jahn, 2015). Furthermore, manufacturing that can be characterized as being centralized is distributed around the world. For example, Toyota's production is distributed in more than 70 factories in more than 25 countries (Schmid and Grosche, 2008a). Another possibility is distributed manufacturing could be argued to be manufacturing that is digitally distributed (Muniain et al., 2015). However, digitalization is a potential enabler for any manufacturing (Rosenbush, 2015).

As these examples illustrate, the distribution of manufacturing is not simply a matter of extent, such as how many factories per square kilometer or mile. Rather, there are different types of manufacturing distributions. Moreover, there are different kinds within different manufacturing distribution types. For example, DIY manufacturing has had different three waves, which exist alongside each other today in subsistence practices, the home assembly of kits, and making at fab labs etc., (Fox, 2014; Toffler, 1980). However, the vagueness of the word, distributed, supports positivist reductionist thinking that reduces complex reality to a flat conjunction of cause and effect (Bullock and Trombley, 2000), such as increasing the number of small factories increases the sustainability of production (Rauch et al., 2016).

In this paper, a taxonomy is introduced to address the inherent vagueness of the adjective distributed, and to facilitate increased specificity in debate concerning alternative manufacturing distributions for sustainable production. In contrast to positivist reductionism, the taxonomy is based on critical realist analysis. Within critical realism, there are multiple layers to causation, with

---

* Corresponding author.
E-mail address: stephen.fox@vtt.fi (S. Fox).

https://doi.org/10.1016/j.jclepro.2017.12.004
0959-6526/© 2017 Elsevier Ltd. All rights reserved.

contextual factors having a determining influence on outcomes (Bhaskar, 1978; Mingers, 2014).

Previous taxonomy research has focused upon categorizing manufacturing organisations with names intended to summarize their strategies, such as Caretakers (Miller and Roth, 1994); Do All (Kathuria, 2000); Servers (Frohlich and Dixon, 2001); and Mass Servers (Zhao et al., 2006). Other studies have focused upon categorizations of sustainability: economic, ecological, social, and institutional (Rauch et al., 2015; Seuring and Müller, 2008). In this paper, by contrast, a taxonomy is presented that categorizes manufacturing in terms of distribution types and their comparative relations to different categories of sustainability.

The remainder of the paper comprises five sections. Next, in Section 2, the research methodology is described. In Section 3, state-of-the-art is set out for different types of manufacturing distributions. In Section 4, case study findings are reported. In Section 5, the taxonomy is introduced. In Section 6, penultimate section, implications are discussed for research and for practice. In Section 7, principal contributions are stated.

Overall, the objective is to provide a taxonomy that facilitates balanced objective consideration of all manufacturing distributions within debate concerning sustainable production.

2. Methodology

The research involved literature review and case study. Throughout, the critical realist perspective was applied of causation having multiple layers, with contextual factors having a determining influence on outcomes (Bhaskar, 1978; Mingers, 2014). Literature review extended from scientific papers and monographs to include online reports etc. The inclusion of this grey literature enables multi-vocal literature reviews, which are necessary when information relevant to a topic is disseminated via diverse media channels (Auger, 1989). Case study was carried out in Turkey, where a wide range of manufacturing distributions are carried out. Turkey has been categorized as an emerging market (Magalhaes, 2013), and it has been claimed that distributed manufacturing has much potential to improve the sustainability of production in emerging markets (Rauch et al., 2016). Field study involved gathering of information by telephone, email, and face-to-face.

3. State-of-the-art for different manufacturing distributions

3.1. Overview

Types of manufacturing distributions identified through literature review are summarized in Fig. 1. Distributed manufacturing is categorized as DIY, artisanal and industrial. DIY manufacturing encompasses the three waves: subsistence (*1*st *wave*) industrial (*2*nd *wave*) and post-industrial (*3*rd *wave*). Artisanal manufacturing encompasses craft-based manufacturing of specialty cheeses, wines, etc., at farms (*rural*), manufacturing at retail outlets such as patisseries, tailors, etc. (*urban*), and manufacturing of easily posted goods by Web-based businesses (*Web*). Industrial distributed manufacturing encompasses manufacturing of components (*parts*); semi knocked-down kits and complete knocked-down kits (*S/CKD*); and complete goods (*products*). Centralized manufacturing includes large scale conversion processes for materials (*large process*), assembly of physically massive complete goods (*large assembly*), clusters of interconnected organizations (*geo cluster*).

3.2. Literature review findings

3.2.1. DIY distributed manufacturing

DIY can be described as having three waves (Fox, 2014; Toffler, 1980). Within subsistence DIY (*1*st *wave*) people make what they need without regularly making purchases in a marketplace. For example, people make their own furniture with rudimentary tools using local natural materials. Within *2*nd *wave* DIY, people buy kits, which are made in factories, for pre-designed boats, furniture, etc., from companies such as Ikea. These kits are sold, for self-assembly (Williams, 2004). Slogans such as personal fabrication, social manufacturing, and maker movement are associated with *3*rd *wave* DIY, which draws upon the read/write functionality of the Internet, and digitally-driven design/manufacture, to enable ordinary people to invent, design, make, and/or sell goods that they think of themselves. *Third wave* DIY includes: original handmade goods advertised and sold globally via Website such as Etsy; small 3D printed goods designed, made, and sold via Websites such as Shapeways; larger goods designed and made via workshops such as Techshops; and vehicles made by organizations such as LocalMotors.com, which combine Web community designing with workshops for vehicle assembly (Fox, 2014). Some *1st wave* DIY subsistence manufacturing is still carried out in Turkey. In villages in Turkey, some local people still make use of arcane practices in their own household production, such as hand making some carpets, other furniture, and food products including cheese and yoghurt (Ates and Ceylan, 2010). By contrast, *2*nd *wave* DIY manufacturing is spreading in Turkey, with the number of DIY retail stores increasing from less than 30 in 2003 to almost 200 in 2015. These stores include Turkish chains such as Koctas and Tekzen, as well as foreign chains such as Bauhaus and Ikea (Kompil and Celik, 2006; Statista, 2016). *Third wave* DIY is also increasing in Turkey using both international and national platforms. For example, in 2016 there are more

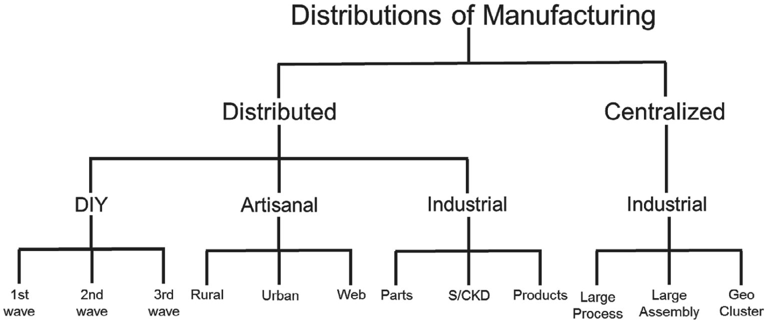


Fig. 1. Distributions of manufacturing.

than 300 Turkish shops being operated via the international 3rd *wave* DIY platform, Etsy. In addition, there are similar Turkish online platforms such as Emeksensin.com and Hobinisat.com (EticaretMag, 2013; Luckman, 2013). For larger scale 3rd *wave* DIY, Fablab have a presence in Turkey. A Turkish variation is the not-for-profit Innocampus.org, which involves mobile makerspaces being transported around Turkey (Gadanski and Čantrak, 2016).

3.2.2. Artisanal distributed manufacturing

Artisanal distributed manufacturing involves production of goods using artisan skills. Often, manufacturing and sales can be combined within one building, such as patisseries and tailors. Such artisanal manufacturing is often located within the shopping streets of towns (*urban*). Other artisanal manufacturing, such as the production of specialty cheeses and fine wines may be located in more rural settings, such as farms and vineyards that incorporate shops (*rural*). More recently, artisanal production can combine Web shops (*Web*) for global sales with traditional artisanal production from one location (Smith, 2009). *Rural* distributed artisanal production is widespread in Turkey. In particular, there are many small family businesses, which continue agricultural production and sales from generation to generation. Notably, olive groves and vineyards are spread across, for example, Turkey's Aegean and Mediterranean regions (Azabagaoglu et al., 2006; Gurbuz et al., 2004). Also, *urban* distributed artisanal production is well-established in Turkey, with towns having their own bakers, furniture makers, and tailors. Recently, *Web*-based artisanal operations have begun in Turkey. For example, Gomlekchim.com is an online platform that customer can use to configure shirt designs from a range of options.

3.2.3. Industrial distributed manufacturing

The contract manufacturing of components (*parts*) is highly distributed around the world (Carbone, 2000; Chan and Chung, 2002). Furthermore, components can be packaged together (*S/CDK*) in semi knocked-down (SKD) kits and completely knocked-down (CKD) kits at an established manufacturing location for subsequent assembly at new manufacturing locations. In either case, a knock-down kit is a kit containing the parts needed to assemble a product (Meyer, 2008). Also, there are some countries where manufacturing of complete goods is carried out, which does not require large scale assembly operations (*products*). A notable example of this are Mittelstand small-to-medium sized enterprises (SME) in Germany. Each company identifies one niche product with a global market and makes the product for export from one factory. Such companies are distributed around Germany (Jahn, 2015). With regard to industrial distributed manufacturing, there are Turkish companies producing parts (*parts*) for car markets. The manufacture of semi and complete knock-down kits (*S/CKD*) is also carried out in Turkey (Yasar, 2013). In addition, the manufacturing of products is carried out by SMEs across several different regions of Turkey: notably in textiles and apparel goods such as garments, rugs, and towels (Kutluksaman et al., 2012).

3.2.4. Centralized manufacturing

Centralized production includes large-scale conversion processes for materials (*large process*), ranging from gold to potassium, which can be concentrated in just one location within a country or even a continent. It can also include production based principally on the supply of materials, such as thorium and uranium, which can be extremely hazardous (Cheng et al., 2000; Kauwenbergh, 2010; Martin, 2009). Also, assembly of physically massive complete goods (*large assembly*) is not well-suited to wide distribution. For example, massive ocean-going cruise liners need to be produced in shipyards large enough to accommodate their production and enable their launching (Shin and Hassink, 2011). In addition, many stages of manufacturing from materials processing to product assembly can be geographically concentrated where there are clusters of interconnected organizations (*geo cluster*). Examples include medical device cluster in Massachusetts USA and apparel cluster in Florence Italy (Beghelli, 2016; Porter, 1998). Some of Turkey's industrial manufacturing is centralized. For example, the city of Zonguldak Ereğli is home to Turkey's largest steel plant, Erdemir (*large process*). The city has a large natural harbour, which is one of the few geographically attractive places for a harbor on the Black Sea coast of Turkey. Erdemir has a production capacity of more than five million tonnes per year of crude steel. It produces plates, hot and cold rolled sheet and tinplate (Mobbs, 2010). Also, *large assembly* operations can be centralized. For example, there is only one factory producing the circular knitting machines for Turkish textile industry, which is TTM Machine located in Central Anatolia (Moment, 2010). In addition, the largest manufacturing geographical cluster in Turkey is the Marmara region (*geo cluster*). It has the natural advantages of being located in northwestern Turkey, with borders to Greece and the Aegean Sea to the west and Bulgaria and the Black Sea to the north (Yasar, 2013).

3.2.5. Summary

Overall, literature review findings indicate that there is a wide range of manufacturing distributions. These can be classified in terms of four types: distributed DIY, distributed artisanal, distributed industrial, and centralized industrial. Furthermore, each of these four types has three kinds of manufacturing distribution: DIY - 1st *wave*, 2nd *wave*, 3rd *wave*; artisanal - *rural, urban, Web*; distributed industrial - *parts, S/CKD, products*; and centralized industrial - *large process, large assembly, geo cluster*. All of these 12 kinds of manufacturing distributions are included in the taxonomy and addressed in the following sections of this paper. By contrast, previous literature has focused on distributed DIY (Anderson, 2012; Fox, 2014) and industrial manufacturing (Raunch et al., 2015, 2016), with centralized industrial being represented as a manufacturing distribution that should be reduced (Gwamuri et al., 2014), and much less consideration being given to artisanal manufacturing (Fox, 2015).

4. Case study – car production in Turkey

A case study was carried out in order to relate different manufacturing distributions to location-specific factors. Car manufacturing was the case because it has been the subject of alternative proposals for distributed manufacturing. For example, it is has been claimed that 3D-printed car, Strati, of 3rd *wave* DIY organization, LocalMotors.com, could lead a manufacturing revolution (Pyper, 2014). On the other hand, industrial carmakers are interested in increasing the distribution of car production through, so called, glocalization. This involves local production around the Globe (Modrak et al., 2015; Schmid and Grosche, 2008b). The case study involved investigation of alternative car manufacturing distributions in Turkey, where car production is seen to provide a means of creating employment (Milliyet, 2014).

Although Turkey does not have its own car brand, it has substantial automotive production with, for example, Honda, Hyundai, Toyota, and ventures with the Turkish manufacturers Otosan, Oyak and Tofas, which include Ford/Otosan, Oyak-Renault, and Tofas/Fiat. In 2017, automotive manufacturing is concentrated in the Marmara region (*geo cluster*). However, the Turkish government seeks to increase manufacturing in the southeastern part of the country by establishing there a new geographical cluster for production (*geo cluster*). In 2015, the Prime Minister of Turkey announced economic stimulus for southeastern Turkey worth approximately 40 billion US dollars. This is because the south-eastern part of Turkey has few job opportunities. Such factors drive internal migration and over population into the Marmara region. The government's target is to establish 80 new factories in southeastern region, which it hopes will create 40,000 new jobs. Companies that move their production plants to these regions will be exempt from corporate tax (Hurriyet, 2016; Karakis, 2016). Important here is the automotive industry, because of its potential to stimulate wide economic activity including the processing of raw materials and manufacture of components (Cincioglu et al., 2012). While this may greatly increase social sustainability in the southeastern Turkey, increases in ecological and economic sustainability are less certain.

For example, when new cars are needed in south-eastern Turkey they are driven some 1200 km by car-carrying truck from Marmara at a 2016 price of about 250 US dollars (USD) per car. This is because car manufacturing in Turkey is centralized in an existing geographical cluster (*geo cluster*) in Marmara. Hitherto, there has not been car production in the southeastern region due to lack of local demand and the relatively small additional price for vehicle delivery of about 250 USD. From an ecological perspective, the impact of transporting 12 cars across some 1200 km on a car-carrying truck is small compared to the total ecological impact of producing 12 cars (Berners-Lee and Clark, 2010). Furthermore, if there is increased car demand in the southeastern region, extending existing factories in the Marmara region could have relatively low ecological impact. This is because necessary roads and other infrastructure have already been constructed in Marmara. Whereas, completely new factories and infrastructure would have to be constructed in the southeastern region.

A wide range of factories, include raw materials processing, could be constructed in the southeastern region. However, subsequent economic and ecological costs of transporting raw materials from the ports of Marmara to the southeast region would be high. Hence, there is little, if any, justification for constructing material processing plants in the southeastern region (*large process*). An alternative would be to construct one large assembly plant in the southeastern region (*large assembly*), and transport parts manufactured in Marmara to there. The break-even for such an investment would depend upon a huge increase in demand in the southeastern region. This is because hundreds of cars per week need to be produced in large-assembly plants.

An alternative would be to construct “mini-factories”for car production across the southeastern region (*products*). This, however, could have higher ecological impact than constructing one large assembly plant. For example, new ground would have to be dug up in more new places. All of this would come at construction costs, which could not equal the economies of scale associated with constructing one large factory at one location (Pica and Archibald, 2015). If the assembly mini-factories were operated with a high level of automation, any sustainability advantages compared to transporting new cars 1200 km from Marmara are unclear. This is because few local manufacturing jobs would be created and the ecological impacts arising from manufacturing and operating automation equipment could be high (Ystgaard et al., 2012). If human workers assembled semi or complete knock-down kits (*S/CKD*), there would at least be the advantage of creating local employment. On the other hand, there would be additional ecological impacts of packaging and protecting the kits as they are transported from the Marmara region (Meyer, 2008). If the manufacturing of parts were carried out in the southeast region (*parts*), there would be the environment and financial costs of transporting processed materials such as steel bars and sheets from Marmara. However, this would create more local employment and boost social sustainability (Karakis, 2016).

Other distributions of manufacturing for automotive production in the southeastern region of Turkey also have few, if any, sustainability advantages compared to transporting completed cars from Marmara. In particular, *1st wave* DIY and *artisanal* production are not relevant. This is because they are not economically viable due to technical constraints and inordinate amount of time required to make cars by hand. *2nd wave* DIY is relevant as consumer car kits are a well-established niche in DIY. However, the ecological impact of transporting a consumer car kit from the ports of Marmara can be at least equal to transporting a completed car. This is because the transportation of complete cars is refined system based on delivery optimization using car-carrying trucks that can move 12 vehicles together. By contrast, transporting consumer car kits involves individual handling and transportation.

Third wave DIY is highly relevant as local options for vehicle production, such as those introduced by LocalMotors.com, are already becoming established in 2017. Those which offer the best improvements for production sustainability are those that involve the least transportation of materials, parts, and kits from the Marmara region, while entailing the most human employment. Such opportunities arise from production based on *3rd wave* DIY open source vehicle designs, which have been developed to make maximum use of standard multi-purpose components. An important feature of *3rd wave* DIY vehicle production is that it is not based on the notion of having to construct fixed factories. Rather, vehicle production can be moved from location to location as needed to meet individual demand as it arises. However, as stated in the summary provided in Table 1, this is no more a perfect solution than any other distribution of manufacturing. Rather, it also brings disadvantages such as limited potential to achieve economies scale equal to those that can be achieved in a fixed geographical cluster.

5. Results - taxonomy of manufacturing distributions

In this section, comparative sustainability analysis is provided for the different manufacturing distribution types and kinds described in Section 3 and summarized in Fig. 1. Then, examples are provided of factors that can affect their comparative sustainability. This is done in terms of the four categories of sustainability: economic, ecological, social, and institutional, which are already used in the distributed manufacturing literature and in other fields also (Rauch et al., 2016, 2015; World Commission on Environment and Development, 1987).

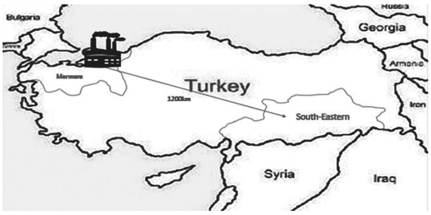
5.1. Types of manufacturing distribution

A comparative sustainability analysis for different manufacturing distributions is summarized in Table 2, and explained in the following paragraphs.

5.1.1. DIY distributed manufacturing

An comparative advantage of *1st wave* DIY subsistence manufacturing is that it involves very little extraction and processing of raw materials. A disadvantage is that it does not bring high standards of living (Easterlin, 2000; Sveiby, 2009). Furthermore, it offers ecological, social, and institutional sustainability only until the arrival of resource hungry people from industrial

Table 1
Advantages and disadvantages of different manufacturing distributions for sustainability.

Scenario	Advantages	Disadvantages
 Transport 12 completed cars about 1200 km from established *Geocluster*	Ecological: close to sources of supply and established demand. Well-developed existing infrastructure. Meeting increases in demand involves little further ecological impact	Social: already a region of full employment and dense population. Hence, the influx of more people to take up new jobs in Marmara can lead to over population
 *Centralized industrial* automotive manufacturing in new large factories	Social: establishing skilled manufacturing jobs can address poverty in the region and prevent further large scale internal migration and over population to Marmara	Ecological: requires large scale construction work followed by the transportation of materials from the ports of north-western Turkey
 *Distributed industrial* automotive manufacturing in new mini-factories	Few if any: this option may serve interests of big brand manufacturers that seek to enter emerging markets, but has no sustainability advantages compared to other options	Sustainability: the construction of many mini-factories can have a higher initial ecological impact. Then, high automation means that few local jobs are created
 *Distributed* 3rd *Wave* DIY automotive manufacturing with moveable factories	Initial ecological: initial low impact because of little need for construction works. Social: some local job creation.	Operating ecological impact: transportation of materials from the ports of north-western Turkey.

societies who destroy the local environment (Gedicks, 1994; Hunn, 1999). An advantage of 2nd *wave* DIY manufacturing is that it can contribute to economic sustainability, because it offers economic savings compared to buying to completed goods. On the other hand, 2nd *wave* DIY encompasses relatively few needs for manufactured goods. Hence, 2nd *wave* DIY cannot make a determining high contribution to economic prosperity. A disadvantage of 2nd *wave* DIY is that it is based upon supply push mass production up to the level of sub-assemblies and assemblies. Hence, its can make only small contributions to improving the ecological sustainability of production (Salvia, 2016; Williams, 2004). Although 3rd *wave* DIY can be dependent upon literacy in lingua franca and having some computer skills, it does introduce new opportunities to break down some barriers to finance and education needed for people to

Table 2
Manufacturing distribution types and their comparative relations to sustainability categories.

Manufacturing distribution		Sustainability		
		Advantages	Disadvantages	References
Distributed DIY	1st wave	Ecological: limited use of raw materials	Economic: low standards of living	Easterlin, 2000; Sveiby, 2009
	2nd wave	Economic: participants reduce their costs	Ecological: based on supply push mass production	Williams, 2004; Ritzer, 2015
	3rd wave	Institutional: traditional access barriers can be broken down	Ecological: based on supply push mass production of materials and parts	Fox, 2014; Salvia, 2016
Distributed Artisanal	Rural	Ecological: reduced animal shipping, post-harvest losses	Sustainability disadvantages can be few	Fox, 2015; Peterson, 2014
	Urban	Social: maintain social fabric of towns and regions	Economic: not competitive with global retailers	Jahn, 2015; Pettypiece, 2016
	Web	Economic: traditional cost barriers broken down	Ecological: extensive use of physical postal services	Canavan et al., 2007; Smith, 2009
Distributed Industrial	Parts	Economic: can create long-term employment	Ecological: based on supply push mass production	Carbone, 2000; Chan and Chung, 2002
	S/CKD	Economic: can stimulate local cluster development	Ecological: non-value adding packaging etc.	Meyer, 2008; Yasar, 2013
	Product	Economic: can create long-term employment	Sustainability disadvantages can be few, but success is hard to reproduce	Dakers, 2017; Jahn, 2015
Centralized Industrial	Large process	Economic: cost efficient materials conversion	Social: offers relatively few jobs and dangerous jobs	Mobbs, 2010; Zakaria et al., 2005
	Large assembly	Social: enables large-scale specialist employment	Disadvantages can be few if close to major sources of supply and demand	Moment, 2010; Shin and Hassink, 2011;
	Geo cluster	Social: large-scale specialist employment	Sustainability disadvantages can be few, but success is hard to reproduce	Beghelli, 2016; Davies and Ellis, 2000

create their own prosperity through manufacturing. Hence, there are some positive implications for economic and social sustainability. However, *3rd wave* DIY can also be based on supply push mass production of many of the components involved. Moreover, successful innovations from *3rd wave* DIY are absorbed into industrial manufacturing (Fox, 2017, 2014).

5.1.2. Artisanal distributed manufacturing

Compared to DIY distributed manufacturing and industrial distributed manufacturing, little consideration has been given to sustainability contributions from artisanal production other than for improvements through increased use of moveable factories (Fox, 2015). An advantage of *rural* distributed artisanal production is that it involves economic value being added directly at the location of supply: especially when moveable factories are used. At the same time, it does not undermine ecological, social or institutional sustainability (Peterson, 2014). *Urban* distributed artisanal production in light industrial estates serves engineer-to-order manufacturing. This is typically less efficient that make-to-stock production in large factories but, on the other hand, seldom involves any inventory of completed goods. *Urban* distributed artisanal production on high streets has the advantage of maintaining the social fabric of small towns. However, it has not been economically sustainable when faced with the lower costs of global retailers such as Walmart (Pettypiece, 2016). *Web*-based distributed artisanal production has the advantage of breaking down traditional barriers to individuals being able to access goods designed in other countries and cultures. However, it has the ecological disadvantage of extensive postage (Canavan et al., 2007; Smith, 2009).

5.1.3. Industrial distributed manufacturing

Distributed industrial manufacturing of *parts* can have the economic sustainability advantage of creating long-term employment that is not necessarily dependent on continued orders from one Original Equipment Manufacturer (Carbone, 2000; Chan and Chung, 2002). At the same time, it can have the disadvantage of being based on supply push mass production. Distributed industrial manufacturing of kits (*S/CKD*) can have the economic sustainability advantage of being a potential starting point for development for local economic clusters (Meyer, 2008). However, both CKD and SKD have the disadvantage of being based on supply push mass production, and also involve extensive non value-adding packaging and protection of volumetric components for transportation to assembly location. Distributed industrial manufacturing of complete goods, which do not require large-scale assembly by SMEs (*products*), has contributed notably to economic and social sustainability in Germany. However, the success of the German Mittelstand have been difficult to reproduce in other countries (Dakers, 2017). Common sustainability claims for industrial distributed manufacturing include the reduction of ecological impact through reducing long distance transportation and reduction of waste arising from centralized production of goods for stock (Mourtzis and Doukas, 2014; Pearce et al., 2010). However, potential negative consequences are often ignored, such as the massive carbon emissions that arise from the long distance formulation, transmission, and storage of increased digital manufacturing data (Schmidt, 2010; Xu, 2012).

5.1.4. Centralized manufacturing

Large-scale conversion operations (*large process*) at the source of materials supply can provide the most economically sustainable opportunities for feeding processed materials into downstream distributed manufacturing. However, there can be serious social disadvantages as automation can leave little human employment, and what employment there is can be dangerous (Zakaria et al., 2005). Centralized assembly of massive products (*large assembly*), such as ocean-going vessels at shipyards, can bring the social advantages of large-scale long-term human employment (Shin and Hassink, 2011). At the same time, if such massive products are to be produced, there may be no more ecologically sustainable alternatives. Similarly, geographical clustering of manufacturing (*geo cluster*) can offer strong economic and social sustainability advantages, such as employment of generations of local people (Beghelli, 2016; Porter, 1998). For example, Turkish car manufacturing is centered in Marmara and much of car production in central Europe has been concentrated around the same region since car production began (Agence France-Presse, 2008; Radosevic and Rozeik, 2005). However, reproducing successful centralized manufacturing, which has arisen due to the particular characteristics of specific locations, may not be possible at other locations with their own particular characteristics (Davies and Ellis, 2000).

5.2. Factors affecting sustainability of all manufacturing distribution types

5.2.1. Economic sustainability

Economic sustainability depends upon sales, and the margin between the prices and the costs of what is sold. For example, continuing to manufacture goods that nobody wants to buy anymore is not economically sustainable - irrespective of the distribution of manufacturing. Conversely, more sustainable production can increase prices on the basis of differentiation, while costs can be reduced if recycled materials are used. For example, sales of music Compact Discs (CD) have plummeted (Straw, 2009). Meanwhile, sales of vinyl records have increased as they have come to be regarded as being a more differentiated product. The individuality of vinyl records can be increased when they are produced in-situ during live music performances by using DIY vinyl cutting lathes that can cut sounds into vinyl grooves as musicians play (Spice, 2017; Sullivan, 2015).

5.2.2. Ecological sustainability

What is inputted, how it is processed, and what is reused have a determining influence on ecological sustainability of production. Much of manufacturing, irrespective of distribution, is dependent upon the large-scale materials extraction, processing, and transportation that is involved in the production of components. This also applies partially to 3D printing, which can be used in 3rd *wave* DIY distributed manufacturing, *artisanal* distributed manufacturing, *industrial distributed* manufacturing. This is because the production of 3D printing powders also requires extensive materials extraction and energy-intensive materials processing (Ji et al., 2017). Thus, much of manufacturing is open to improvements in ecological sustainability brought about international actions in pollution abatement (Gurtu et al., 2016). At the same time, different types of manufacturing distributions can benefit from different initiatives and methods. For example, 2nd *wave* DIY can benefit from Ikea's reduction of waste and increase use of renewable energy in production processes (Freudenthal, 2016). Meanwhile, 3rd *wave* DIY can benefit from individuals putting together their own Recyclebots in order to convert waste plastic into filament for open-source 3D printers (Baechler et al., 2013).

5.2.3. Social sustainability

With regard to social sustainability, this can be increased through equal opportunities to participate, social ownership, and community engagement (Boyle and Simms, 2009; Matthews, 1999). For example, the Mondragon industrial cooperative is in a *geocluster.* By contrast, another cooperative, Arla Foods, involves industrial distributed manufacturing (Clamp and Alhamis, 2010). However, irrespective of ownership, social sustainability could be reduced when manufacturing involves such high levels of automation that human operatives are not needed. Levels of factory automation are increasing rapidly in around the world. For example, Petlas Tire Corporation's factory in Kirsehir, Turkey is implementing a fully automated handling system for its tire production (Tyrepress, 2016). In some cases, human presence is so little that lights are turned off. Hence, the emergence of terms such as “lights out” manufacturing (Bogue, 2014). Hitherto, automation has been concentrated in large factories. However, more versatile lower cost automation is continually being developed that can be used in smaller scale manufacturing (Srai et al., 2016; Woollacott, 2017).

5.2.4. Institutional sustainability

Institutions are stable, recurring, valued patterns of behavior among individuals within a community. Institutions can be informal as practices and/or formal as legal entities (Lawrence and Suddaby, 2006). Institutional sustainability is concerned with ethics. For example, The Ethical Fashion Forum (EEF) holds that ethical fashion represents an approach to the manufacture of clothing, which maximises benefits to people and communities while minimising impact on the environment (Jahdi et al., 2017). At the same time, institutional sustainability encompasses different viewpoints of different cultures in the framing of what is ethical (Oskarsson, 2017). Moreover, institutional sustainability is also concerned with organizations being accountable for unethical practices (Milne and Gray, 2013), such as breach of labour conventions (Theuws and Overeem, 2014). Overall, long-established debates about opportunity and exploitation are relevant to different manufacturing distributions. For example, it has been argued that DIY manufacturing provides opportunities for individuals to express themselves creatively, while saving money and even setting-up enterprises. By contrast, others have argued that DIY manufacturing involves individuals being exploited as they carry out unpaid work that boosts the growth of established for-profit organisations (Ritzer, 2015; Zwick et al., 2008).

5.3. Taxonomy

The sustainable production taxonomy is shown in Fig. 2. This brings together in a single diagrammatic format: the summary of different manufacturing distributions (Fig. 1), the sustainability analysis of manufacturing distributions (Table 2), and the description of factors affecting sustainability categories in Section 5.2. As production sustainability is affected by many factors, no manufacturing distributions are shown to have inherently high sustainability in the taxonomy. Rather, production sustainability is dependent upon lasting sales demand at viable margins arising from positive difference between prices and costs, which are based on ecologically-friendly inputs, processes and reuse that encompasses wide social participation, ownership, and engagement with ethical, inclusive and accountable practices.

As indicated by the black, dark grey, and light grey symbols in Fig. 2, it is possible for there to be a high, medium, or low probability of sustainability for each factor. As indicated by the white symbol for Fig. 2, assessment of probabilities should be made through situation-specific critical realist analyses, which address multiple layers of causation including contextual factors (Bhaskar, 1978; Mingers, 2014). Extensive details about how to carry out critical realist studies can be found in numerous publications (e.g. Fox, 2013; Wynn and Williams, 2012).

When carrying out assessments, it is necessary to gather information related to all aspects of production sustainability shown in Fig. 2. At the same time, it is important to apply techniques that can be used to reduce potential for bias. For example, balance can be increased by taking middle ground between positive and negative forecasts of sustainability (Fox, 2012). Negative forecasts can be facilitated by application of techniques such as devils advocacy (Walker, 2004) and negative brainstorming (West, 2003). Here, it is important to note that negative forecasts (e.g. worse case scenarios) are rarely negative enough (Kahneman et al., 2011). For example, there is considerable hype about 3rd *wave* DIY. However, the 3rd *wave* DIY enterprise of one of its leading advocates, who claimed that 3rd *wave* DIY would bring a new industrial revolution (Anderson, 2012), soon became bankrupt (Mac, 2016). Similarly, the high profile chain of 3rd *wave* DIY workshops, Techshop, became bankrupt at the end of 2017 (Malone, 2017). Thus, contributions to sustainable production were limited.

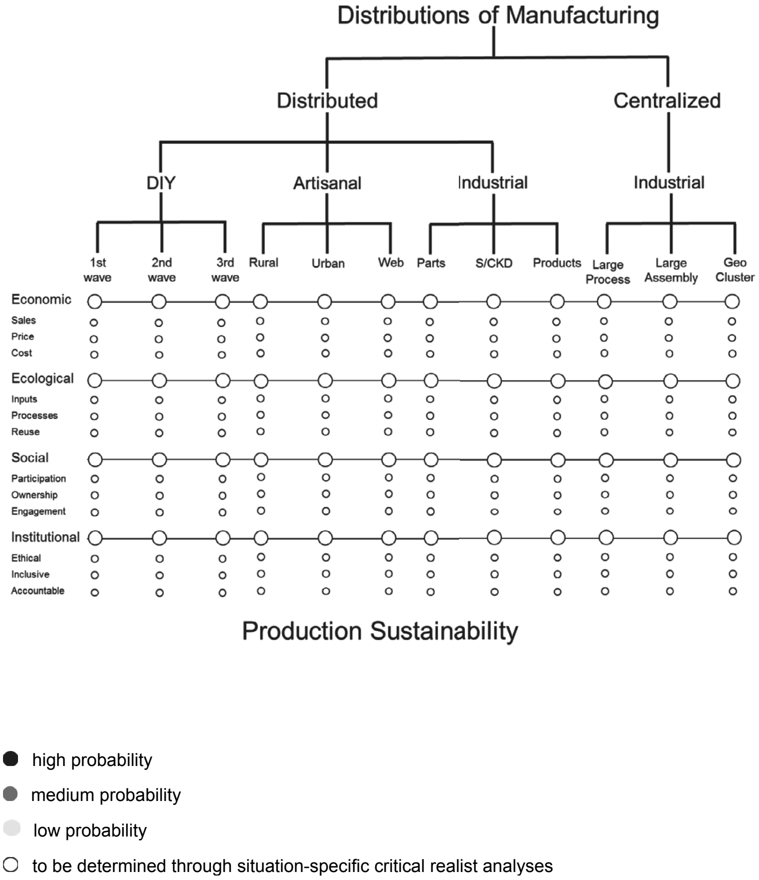


Fig. 2. Taxonomy of manufacturing distributions.

A comparison of two alternative options is illustrated by Fig. 3. This shows a comparison of two options for agri-food production: artisanal *rural* production versus industrial *large process* production. In particular, the use of artisanal rural production enabled by mobile factories is increasing (eXtension Foundation, 2017). With regard to economic sustainability, sales volumes are comparatively low. However, the use of mobile factories enables the production authenticity and integrity of food from farm-to-table, which can attract prices double those for mass produced agri-food products (Peterson, 2014). The marginal costs of artisanal production can be far higher than those of industrialised large processes. On the other hand, capital investment costs can be far lower (Fox, 2015). Artisanal production with mobile factories offer the ecological benefits of reducing harm caused by transportation of live animals, and other post-harvest losses (Kitinoja and Kader, 2003). Also, artisanal production with mobile factories is often a cooperative enterprise with diverse participation, ownership and engagement (eXtension Foundation, 2017). At the same time, artisanal production can be motivated by concerns for ethical and inclusive production (SARE, 2006). On the other hand, accountability can be more difficult to establish for many mobile factories compared to one *large process* plant. Moreover, even if *large process* plants are set-up solely for profit, they need to comply with regulations concerned with ecological, social, and institutional sustainability (Milne, and Gray, 2013; Ralston et al., 2015). Thus, each kind of distribution has comparative strengths and weaknesses. Furthermore, the interplay between factors that affect production sustainability are dynamic not fixed. For example, the integrity of *rural* artisanal production can be undermined by side effects from genetic modification in industrial agricultural production (Huffman, 2004; Marsden and Smith, 2005).

As illustrated by Fig. 3, assessment of probabilities should be made through situation-specific critical realist analyses, which address the multiple layers of causation including contextual factors that have a determining influence on outcomes (Bhaskar, 1978; Mingers, 2014).

6. Discussion

6.1. Implications for research

Distributed is an inherently vague word with indeterminate boundaries. Vagueness limits causal explanation and can lead to positivist reductionist assertions that present an option as having sweepingly positive effects. At the same time, proponents can

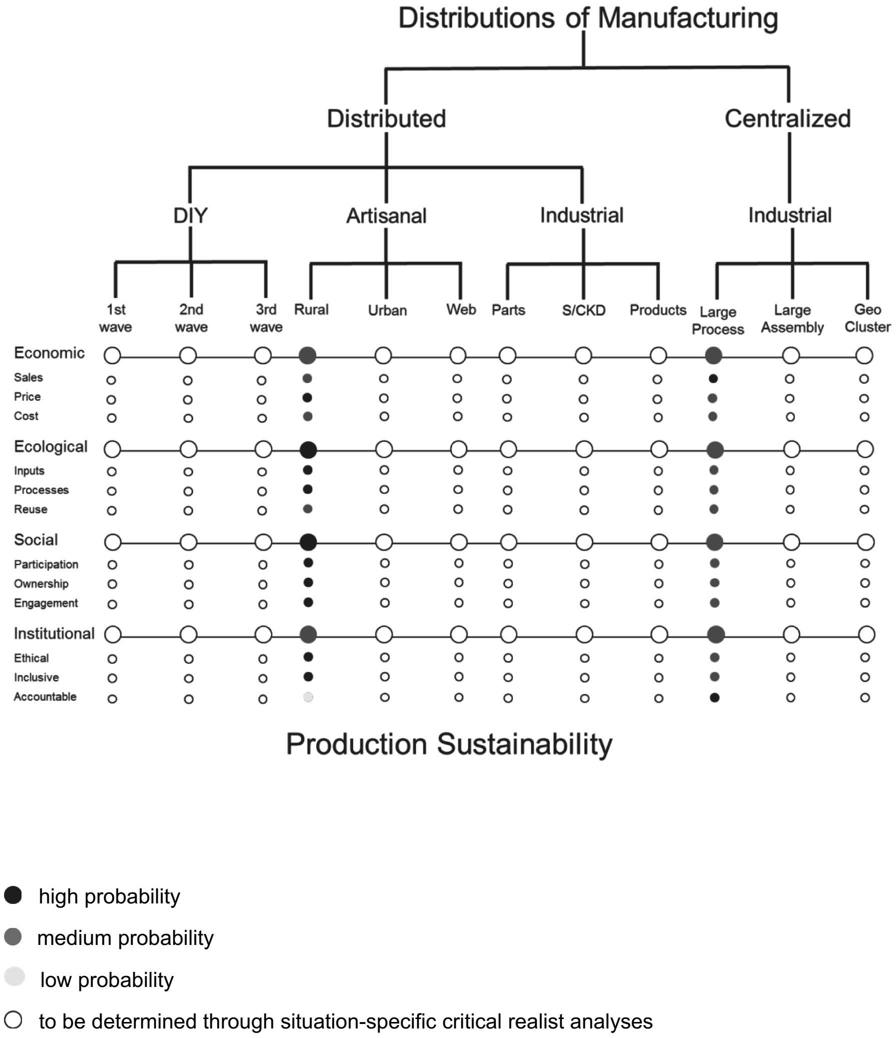


Fig. 3. Taxonomy of manufacturing distributions example: Agri-food production.

argue fallacies of single cause and incomplete evidence, which involve cherry picking particular aspects of special cases (Pohl, 2004). For example, goods made of one material that can often be locally sourced, such as furniture made of wood, are used to argue for increasing the distribution of industrial manufacturing (Meyerson, 2015). However, goods often comprise many different materials, which can seldom be locally-source (Bartekováa and Kemp, 2016).

Furthermore, vagueness in discussions of manufacturing distributions can obscure the relevance of well-establish theories. For example, manufacturing distributions have long been analyzed within economic geography studies (Coe, 2012; Ohuallachain, 1992). Such analyses indicate that there are many advantages for production sustainability from the concentration of manufacturing in *geo clusters* at a few locations (Beghelli, 2016; Porter, 1998). Yet, the success of *geo clusters* can be very difficult to reproduce. Thus, previous research indicates is what works well at one location does not work well at another location (Davies and Ellis, 2000). Accordingly when considering the potential sustainability of alternative manufacturing distributions, it is appropriate to apply the critical realist perspective that there are multiple layers to causation with contextual factors have a determining influence on outcomes (Bhaskar, 1978; Mingers, 2014).

6.2. Implications for practice

From a practical perspective, the taxonomy goes beyond location appraisal methods (Nagy and Salhi, 2007; Yang and Lee, 1997). This is because the taxonomy encompasses four different manufacturing distributions, which together include 12 kinds of manufacturing distributions. Moreover, the taxonomy encompasses comparative relations to four categories of production sustainability. The taxonomy offers several advantages for both intuitive thinking and deliberative thinking. With regard to intuitive thinking, such diagrammatic representations are better than other formats for summarizing interrelationships, while presenting an holistic overview (Vessey, 1991). This is because they are simple representations of multiple factors that can require minimum cognitive effort to grasp and to recall, while providing explanation of causation that incorporates several points of view simultaneously (Huang et al., 2006). For deliberative thinking, the succinct statements of types, kinds, and categories can be entry points for more detailed descriptions. These details can be presented in any communicative format (Seufert, 2003).

7. Conclusions

Specificity is needed in definition of manufacturing distributions when discussing options for improving production sustainability. In this paper, a taxonomy of manufacturing distributions has been introduced. Previous literature has focused on DIY manufacturing and industrial manufacturing, with centralized manufacturing being represented as a manufacturing distribution that should be reduced, and much less consideration being given to artisanal production. By contrast, the taxonomy of manufacturing distributions introduced in this paper encompasses three kinds within each of four types of manufacturing distributions: DIY, artisanal, industrial, and centralized manufacturing.

It is argued that different manufacturing distributions have comparative strengths and weaknesses. This is because literature review and case study reveal little compelling evidence that any one distribution of manufacturing will inevitably increase the sustainability of production: especially in the long-term. Rather, production sustainability is affected by many inter-related factors. Moreover, there are examples where centralizing manufacturing, especially in geo clusters, can be the most sustainable option. If objective balanced research across a range of settings reveals that a particular manufacturing distribution brings increased production sustainability than is currently shown in the taxonomy, then the taxonomy can be amended accordingly. However, the burden of proof is upon those who assert that increasing a particular manufacturing distribution will inevitably increase production sustainability.

Objective balanced research should address all categories of production sustainability: economic, ecological, social, and institutional. In doing so, every factor contributing to each category of production sustainability should be considered. For example, despite hype about 3rd *wave* DIY, some high profile 3rd *wave* DIY organizations have not been economically sustainable and have gone into bankruptcy because of lack of sales demand at viable margins. Hence, their potential advantages for ecological, social, and institutional sustainability are not realized. This example illustrates that strength in some categories of production sustainability does not compensate for weakness other categories. Hence, claims for production sustainability arising from manufacturing distribution should be moderated by critical realist analyses that encompass balanced assessment of all aspects of sustainability.

References

Agence France-Presse, 2008. Slovak car industry production almost doubled in 2007: World's largest production of cars per capita. Ind. Week. April 8.

Anderson, C., 2012. Makers: The New Industrial Revolution, Crown Business. Random House Inc, New York, NY.

Ardalan, D., 2017. Meet Urban Manufacturers Leading The "Made In New York" Charge. The Huffington Post. May 31.

Ates, H.C., Ceylan, M., 2010. Effects of socio-economic factors on the consumption of milk, yoghurt, and cheese: insights from Turkey. Br. food J. 112 (3), 234–250.

Auger, C.P., 1989. Information Sources In Grey Literature, second ed. Bowker, London.

Azabagaoglu, M.O., Akyol, A., Ozay, A., 2006. Examining the Turkish wine industry: marketing effectiveness and recommendations for increasing its competitive performance. N. Z. J. Crop Hortic. Sci. 34, 257–268.

Baechler, C., DeVuono, M., Pearce, J.M., 2013. Distributed recycling of waste polymer into RepRap feedstock. Rapid Prototyp. J. 19 (2), 118–125.

Barteková́a, E., Kemp, R., 2016. National strategies for securing a stable supply of rare earths in different world regions. Resour. Policy 49, 153–164.

Beghelli, C., 2016. Nearly one quarter of italy's fashion industry clusters hit a new record for exports last year. Il sole 24 ore. April 28.

Berners-Lee, M., Clark, D., 2010. What's the carbon footprint of a new car? The guardian. September 23.

Bhaskar, R.A., 1978. Realistic Theory Of Science. Harvester Press, Brighton.

Bogue, R., 2014. What future for humans in assembly? Assem. Autom. 34 (4), 305–309.

Boyle, D., Simms, A., 2009. The New Economics: A Bigger Picture. Taylor & Francis, New York.

Bullock, A., Trombley, S., 2000. The New Fontana Dictionary Of Modern Thought. HarperCollins, New York.

Canavan, O., Henchion, M., O'Reilly, S., 2007. The use of the internet as a marketing channel for Irish speciality food. IJRDM 35 (2), 178–195.

Carbone, J., 2000. What buyers look for in contract manufacturers. Purchasing 128 (4), 33–38.

Chan, M.F.S., Chung, W.W.C., 2002. A framework to develop an enterprise information portal for contract manufacturing. Int. J. Prod. Econ. 75, 113–126.

Cheng, H., Edwardsa, R.L., Hoffa, J., Gallupb, C.D., Richardsc, D.A., Asmeromd, Y., 2000. The half-lives of uranium-234 and thorium-230. Chem. Geol. 169 (1–2), 17–33.

Cincioglu, E., Onsel, S., Ulengin, F., 2012. Competitiveness analysis of automotive industry in Turkey. Expert Syst. Appl. 39 (12), 10923–10932.

Clamp, C.A., Alhamis, I., 2010. Social entrepreneurship in the mondragon cooperative corporation and the challenges of successful replication. J. Entrep. 19 (2), 149–177.

Coe, N.M., 2012. Geographies of production II: a global production network A–Z. Prog. Hum. Geog 36 (3), 389–402.

Dakers, M., 2017. The Power Of Germany's Mittelstand. The Telegraph. May, 11.

Davies, H., Ellis, P., 2000. Porter's competitive advantage of nations: time for the final judgement? J. Manage. Stud. 37 (8), 1188–1213.

Easterlin, R.A., 2000. The worldwide standard of living since 1800. J. Econ. Perspect 14 (1), 7–26.

EticaretMag, 2013. El Yapımı Ürün Satan Türk E-ticaret Siteleri (Turkish E-commerce Websites Which Sell Handmade Products). January 18. http://eticaretmag.com/el-yapimi-urun-satan-turk-e-ticaret-siteleri/.

eXtension Foundation, 2017. Slaughter/Processing Units Currently In Operation. In: http://articles.extension.org/pages/19781/mobile-slaughterprocessing-unitscurrently-in-operation.

FEDIYMA, 2016. World DIY Report 2015. European Federation of DIY Manufacturers, Cologne/Germany.

Fox, S., 2012. Improving new product development by screening manufactured goods for potential disbenefits and negative consequences. J. Manuf. Technol. Manag. 23 (5), 615–633.

Fox, S., 2013. Getting real about ICT: applying critical realism to the framing of information and communication technologies. Manag. Res. Rev. 36 (3), 296–319.

Fox, S., 2014. Third Wave Do-It-Yourself (DIY): potential for prosumption, innovation, and entrepreneurship by local populations in regions without industrial manufacturing infrastructure. Technol. Soc. 39, 18–30.

Fox, S., 2015. Moveable factories: how to enable sustainable widespread manufacturing by local people in regions without manufacturing skills and infrastructure. Technol. Soc. 42, 49–69.

Fox, S., 2017. Mass imagineering, mass customization, mass production: complementary cultures for creativity, choice and convenience. J. Consum. Cult. https://doi.org/10.1177/1469540517705945. May 10.

Freudenthal, C., 2016. IKEA Group Sustainability Report 2016. IKEA, Leiden, NL.

Frohlich, M.T., Dixon, J.R., 2001. A taxonomy of manufacturing strategies revisited. J. Oper. Manag. 19 (5), 541–558.

Gadanski, I., Čantrak, D., 2016. Kickstarting the fab lab ecosystem in Serbia. In: Sci-FabLab and FABelgrade Conference. https://doi.org/10.1109/MEDO.2016.7746541. Belgrade, Serbia.

Gedicks, A., 1994. The New Resource Wars: Native and Environmental Struggles against Multinational Corporations. Black Rose Books Ltd, Cheektowaga, NY.

Gurbuz, S., Kiran, N., Yenigun, O., 2004. Cleaner production implementation through process modifications for selected SMEs in Turkish olive oil production. J. Clean. Prod. 12 (6), 613–621.

Gurtu, A., Searcy, C., Jaber, M.Y., 2016. A framework for reducing global manufacturing emissions. J. Environ. Dev. 25 (2), 159–190.

Gwamuri, J., Wittbrodt, B.T., Anzalone, N.C., Pearce, J.M., 2014. Reversing the trend of large scale and centralization in manufacturing: the case of distributed manufacturing of customizable 3D printable self-adjustable glasses. Challenges Sustain. 2 (1), 30–40.

Huang, Z., Hsinchun, C., Guo, F., Xu, J.J., Wu, S., Chen, W.-H., 2006. Expertise visualization: an implementation and study based on cognitive fit theory. Dec Support Syst. 42, 1539–1557.

Huffman, W.E., 2004. Production, identity preservation, and labeling in a marketplace with genetically modified and non-genetically modified foods. Plant Physiol. 134 (1), 3–10.

Hunn, E., 1999. The value of subsistence for the future of the world. In: Nazarea, V.D. (Ed.), Ethnoecology: Situated Knowledge/located Lives. University of Arizona Press, Tucson, pp. 23–36.

Hurriyet, 2016. Prime Minister Yıldırım Announces New Investment Package for Eastern Turkey. Invest in Turkey. September 6.

Jahdi, K.S., Poldner, K., Koehler, K., 2017. Ethical fashion: an exploratory research. In: Aluchna, M., Idowu, S. (Eds.), The Dynamics of Corporate Social Responsibility Springer International Publishing, pp. 221–236.

Jahn, V., 2015. The Importance of Mittelstand Firms for Regional Apprenticeship Activity: Lessons for Policy (No. 158). Diskussionspapier, Helmut-Schmidt-Universität, Fächergruppe Volkswirtschaftslehre.

Ji, L., Wang, C., Wu, W., Tan, C., Wang, G., Duan, X.M., 2017. Spheroidization by plasma processing and characterization of stainless steel powder for 3D printing. Metall. Mater. Trans. A 1–11.

Kahneman, D., Lovallo, D., Sibony, O., 2011. Before you make that big decision. Harv. Bus. Rev. 89 (6), 50–60.

Karakis, G., 2016. Yilda 80 Fabrika Kurulacak (80 Factories Will Be Established in a Year). Hurriyet. September 5.

Kathuria, R., 2000. Competitive priorities and managerial performance: a taxonomy of small manufacturers. J. Oper. Manag. 18 (6), 627–641.

Kauwenbergh, S., 2010. World Phosphate Rock Reserves and Resources. Int. Fertilizer Development Center (IFDC), Muscle Shoals, Alabama.

Kitinoja, L., Kader, A.A., 2003. Small-scale Postharvest Handling Practices: a Manual for Horticultural Crops, fourth ed. Postharvest Technology Research and Information Center, University of California, Davis.

Kohtala, C., 2015. Addressing sustainability in research on distributed production: an integrated literature review. J. Clean. Prod. 106, 654–668.

Kompil, M., Celik, H.M., 2006. Modelling the spatial consequences of retail structure change of Izmir-Turkey. June 1–2. In: Int. Conf. Regional and Urban Modelling. Brussels Free University, Brussels.

Kutluksaman, M., Mutlu, I., Unluaslan, E., 2012. Turkey's textiles and apparel cluster microeconomics of competitiveness. Institute for Strategy & Competitiveness, Harvard Business School.

Lawrence, T.B., Suddaby, R., 2006. Institutions and institutional work. In: Clegg, S., Hardy, C., Lawrence, T. (Eds.), Handbook of Organization Studies, second ed. Sage, London, pp. 215–254.

Luckman, S., 2013. The aura of the analogue in a digital age: women's crafts, creative markets and home-based labour after Etsy. Cult. Stud. Rev. 19, 249–270.

Mac, R., 2016. Behind The Crash of 3d Robotics, North America's Most Promising Drone Company. Forbes. October 5.

Magalhaes, L., 2013. O'neill, Man Who Coined 'Brics,' Still Likes Brics, But Likes Mints, Too. Wall str. j. December 9.

Malone, E., 2017. Mourning The Loss Of Techshop. Make Magazine. November 16.

Marsden, T., Smith, E., 2005. Local Branding Geoforum Ecol. Entrepreneursh. Sustain. Dev. Local communities Thro. Qual. food Prod. 36 (4), 440–451.

Martin, R., 2009. Uranium Is So Last Century – Enter Thorium, The New Green Nuke. Wired. September 21.

Matthews, R., 1999. Jobs Of Our Own: Building A Stakeholder Society. Fernwood Publishing Black Point, Nova Scotia, Canada.

Meyer, T., 2008. Selection criteria: assessing relevant trends and indicators. In: Abele, E., Meyer, T., Näher, U., Strube, G., Sykes, R. (Eds.), Global Production. A Handbook for Strategy and Implementation. Springer, Berlin, Heidelberg, pp. 34–101.

Meyerson, B., 2015. Emerging Tech 2015: Distributed Manufacturing. World Econ. Forum. March 4.

Miller, J.G., Roth, A.V., 1994. A taxonomy of manufacturing strategies. Manag. Sci. 40 (3), 285–304.

Milliyet, 2014. Konya'nin Otomobil Fabrikasi Hayali (Konya's Car Factory Dream). June 25.

Milne, M.J., Gray, R., 2013. W(h)ither ecology? The triple bottom line, the global reporting initiative, and corporate sustainability reporting. J. Bus. Ethics 118 (1), 13–29.

Mingers, J., 2014. Systems Thinking, Critical Realism And Philosophy: A Confluence Of Ideas. Routledge, Abingdon, OX.

Mobbs, P.M., 2010. The mineral industry of turkey, in: minerals yearbook. V 3. Area Reports. Geological Survey, U.S., p. 56

Modrak, V., Bednar, S., Marton, D., 2015. Generating product variations in terms of mass customization. In: Applied Machine Intelligence and Informatics (SAMI), 13th Int. Symp. IEEE, pp. 187–192.

Moment, 2010. Türkiye De Tek Dünyada 7 Firmadan Biri (It Is Unique In Turkey, One Of The Seven Firm In World), pp. 12–13. Moment, August 27.

Mourtzis, D., Doukas, M., 2014. Design and planning of manufacturing networks for mass customisation and personalisation: challenges and outlook. Procedia CIRP 19, 1–13.

Muniain, J.Z., Valente, A., Dhokia, V., 2015. Dematerialized manufacturing systems. Int. J. Comp. Integ. Manuf. 28 (4), 337–338.

Nagy, G., Salhi, S., 2007. Location-routing: issues, models and methods. Eur. J. Oper. Res. 177 (2), 649–672.

Ohuallachain, B., 1992. Industrial-geography. Prog. Hum. Geog 16 (4), 545–552.

Oskarsson, P., 2017. Diverging discourses on bauxite mining in Eastern India: life-supporting hills for adivasis or national treasure chests on barren lands? Soc. Nat. Resour. 30 (8), 1–15.

Pearce, J.M., Blair, C.M., Laciak, K.J., Andrews, R., Nosrat, A., Zelenika-Zovko, I., 2010. 3D printing of open source appropriate technologies for self-directed sustainable development. J. Sustain. Dev. 3, 17–29.

Peterson, H., 2014. People Are Paying Twice As Much For Meat Processed By This Mobile Slaughter House. Business Insider august 5.

Pettypiece, S., 2016. Wal-Mart: It Came, It Conquered, Now It's Packing Up And Leaving. Bloomberg News january 25.

Pica, M.M., Archibald, R.D., 2015. Project Life Cycle Economics: Cost Estimation, Management And Effectiveness In Construction Projects. Gower Publishing, Farnham, UK.

Pohl, R., 2004. Cognitive Illusions: A Handbook On Fallacies And Biases In Thinking, Judgement And Memory. Psychol. Press, New York.

Porter, M.E., 1998. Clusters and the new economics of competition. Harv. Bus. Rev. 76 (6), 77–90.

Pyper, J., 2014. ClimateWire: world's first three-dimensional printed car made in chicago: an Arizona company is the first to use 3-D printing to make a car. Sci. Am. 12.

Radosevic, S., Rozeik, A., 2005. Foreign Direct Investment And Restructuring In The Automotive Industry In Central And East Europe (Economics working papers 53). Centre For Study Of Social and Economic Change in Europe, SSEES, UCL, London.

Ralston, D.A., Egri, C.P., Karam, C.M., Naoumova, I., Srinivasan, N., Casado, T., Li, Y., Alas, R., 2015. The triple-bottom-line of corporate responsibility: assessing the attitudes of present and future business professionals across the BRICs. Asia Pac. J. Manag. 32 (1), 145–179.

Rauch, E., Dallingera, M., Dallasega, P., Matt, T.D., 2015. Sustainability in manufacturing through distributed manufacturing systems (DMS). Procedia CIRP 29, 544–549.

Rauch, E., Dallasega, P., Matt, T., 2016. Sustainable production in emerging markets through distributed manufacturing systems (DMS). J. Clean. Prod. 135, 127–138.

Ritzer, G., 2015. Prosumer capitalism. Sociol. Quart. 56 (3), 413–445.

Rosenbush, S., 2015. Small Firms Get New Manufacturing Edge: 3-D Printing In The Cloud. Wall str. j. May 26.

Salvia, G., 2016. The satisfactory and (possibly) sustainable practice of do-it-yourself: the catalyst role of design. J. Des. Res. 14 (1), 22–41.

SARE, 2006. Final Report For Fnc05-584: Design And Pilot A State Approved Mobile Slaughter Trailer For Halal Custom Slaughter. Sustainable agriculture research & education. University of Maryland, College Park, MD.

Schmid, S., Grosche, P., 2008a. Managing The International Value Chain In The Automotive Industry: Strategy, Structure, And Culture. Bertelsmann-Stiftung, pp. 11–52.

Schmid, S., Grosche, P., 2008b. Glocal Value In The Volkswagen Group: Towards More Decentralization Of Production And Development (Glokale Wertschopfung Im Volkswagen-Konzern - Auf Dem Weg Zu Mehr Dezentralisierung Bei Produktion Und Entwicklung). European School of Management, Berlin. ESCPEAP Working Paper n. 41.

Schmidt, S., 2010. The Dark Side Of Cloud Computing: Soaring Carbon Emissions. The Guardian. April 30.

Seufert, T., 2003. Supporting coherence formation in learning from multiple representations. Learn. Instr. 13 (2003), 227e237.

Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. J. Clean. Prod. 16 (15), 1699–1710.

Shin, D.H., Hassink, R., 2011. Cluster life cycles: the case of the shipbuilding industry cluster in South Korea. Reg. Stud. 45 (10), 1387–1402.

Smith, P., 2009. A Suit That Fits Is Cutting Its Cloth To Profit From Recession. Telegraph. January 6.

Sorensen, R., 2006. Vagueness and the Logic of Ordinary Language. In: Jacquette, D. (Ed.), Philosophy of Logic. Elsevier, pp. 919–935.

Spice, A., 2017. Soho Radio Installs Vinyl Lathe To Cut Sessions By Seun Kuti & More Direct-To-Disc. The vinyl factory magazine march 23.

Srai, J.S., Kumar, M., Graham, G., Phillips, W., Tooze, J., Ford, S., Beecher, P., Raj, B., Gregory, M., Tiwari, M.K., Ravi, B., Neely, A., Shankar, R., Charnley, F., Tiwari, A., 2016. Distributed manufacturing: scope, challenges and opportunities. Int. J. Prod. Res. 54, 6917–6935.

Statista, 2016. number of diy retail stores in turkey from 2003 to 2015. https://www.statista.com/statistics/456096/diy-retailers-number-of-stores-turkey/.

Straw, W., 2009. The music CD and its ends. Des. Cult. 1 (1), 79–91.

Sullivan, C., 2015. Uk Vinyl Boom Sends Prices Spinning Into 'Premium' Territory. The Guardian. October 13.

Sveiby, K.-E., 2009. Aboriginal principles for sustainable development as told in traditional law stories. Sustain. Dev. 17 (6), 341–356.

Theuws, M., Overeem, P., 2014. Flawed Fabrics: The Abuse Of Girls And Women Workers In The South Indian Textile Industry. Centre for Research on Multinational Corporations and India Committee of the Netherlands.

Toffler, A., 1980. The Third Wave. William Morrow and Co., Inc., New York.

Tyrepress, 2016. Cimcorp Supplying Automated Handling System To Petlas. November 9.

Vessey, I., 1991. Cognitive fit: a theory-based analysis of the graphs versus tables literature. Dec Sci. 22, 219–240.

Walker, S., 2004. Socratic strategies and devil's advocacy in synchronous CMC debate. J. Comput. Assisted Learn. 20, 172–182.

West, M., 2003. Effective Teamwork: Practical Lessons From Organizational Research. Blackwell, Oxford.

Williams, C.C., 2004. A lifestyle choice? Evaluating the motives of do-it-yourself (DIY) consumers. IJRDM 31 (5), 270–278.

Woollacott, E., 2017. Factory Of The Future Is Computerized Intelligence. Raconteur. June 28.
World Commission on Environment and Development, 1987. Our Common Future. Oxford University Press, Oxford.
Wynn, D., Williams, C.K., 2012. Principles for conducting critical realist case study research in information systems. MIS Q. 36 (3), 787–810.
Xu, X., 2012. From cloud computing to cloud manufacturing. Robot. Comp. Integ. Manuf. 28 (1), 75–86.
Yang, J., Lee, H., 1997. An AHP decision model for facility location selection. Facilities 15 (9/10), 241–254.
Yasar, O., 2013. Automotive main and component industries in Turkey and clustering in the Marmara Region. Int. Period. for the Lang. Literature Hist. Turkish or Turkic 8 (6), 787–801.
Ystgaard, P., Gjerstad, T.B., Lien, T.K., Nyen, P.A., 2012. Mapping Energy Consumption for Industrial Robots. Leveraging technology for a sustainable world. In: Proceedings of the 19th CIRP Conference on Life Cycle Engineering. University of California at Berkeley, Berkeley, USA, pp. 251–256. May 23–25.
Zakaria, A.M., Noweir, K.H., El-Maghrabi, G., 2005. Evaluation of occupational hazards in foundries. J. Egypt. Publ. Health Assoc. 80 (3–4), 433–462.
Zhao, X., Sum, C.C., Qi, Y., Zhang, H., Lee, T.S., 2006. A taxonomy of manufacturing strategies in China. J. Oper. Manag. 24 (5), 621–636.
Zwick, D., Bonsu, S.K., Darmody, A., 2008. Putting consumers to work: Co-creation and new marketing governmentality. J. Cons. Cult. 8 (2), 163–196.