TAMPERE UNIVERSITY OF TECHNOLOGY

**ANSSI NURMI**

# BUSINESS MODELS AND APPLICATIONS FOR MICRO AND DESKTOP PRODUCTION SYSTEMS

## MASTER OF SCIENCE THESIS

Prof. Petri Suomala and Prof. Reijo Tuokko have been appointed as the examiners at the Council Meeting of the Faculty of Business and Technology Management on January 11, 2012.

# ABSTRACT

**TAMPERE UNIVERSITY OF TECHNOLOGY**
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The terms microfactory and desktop factory originates from Japan in the 1990’s. Small machines were developed to produce small parts and save resources. In the late 1990’s, the research spread around the world, and multiple miniaturized concepts were introduced. However, the level of commercialization remains low. More empirical evidence and business aspect is needed. This thesis discusses how the systems can be used and how the providers benefit of it, now and in the future. The research includes 18 semi-structured interviews in Europe. The interviewees are both from academic and industry, including equipment and component providers, and users and potential users.

According to the interviews, research and the industry have different viewpoints to the miniaturization. Within the academics, miniaturization links to a general philosophy to match the products in size. In the industry, the small size is only a secondary sales argument. The main factors preventing breakthrough are the lack of small subsystems, the lack of examples and production engineers’ attitudes. It appears that the technology is in the beginning of the S-curve, and it has systematic development as well as slow technology diffusion. More cooperation and a large scale demonstration are needed.

In the literature, there are multiple applications. The MEMS industry is stated as one promising industry. The research aims usually for high level of automation. Based on interviews, the systems are used as a semi-automatic tool for component manufacturing and assembly. In the future, educational and laboratory use as well as prototyping are promising. Local cleanrooms interest but questions arise. In addition, retail level personalization, home fabrication and the MEMS industry include problems. For providers, the technology offers two promising customer segments (Lean manufacturers and fully loaded factories), few additional segments (e.g. educational, laboratories and offices) and it eases some alternative charging models (e.g. leasing, and capacity sales).

# TIIVISTELMÄ

**TAMPEREEN TEKNILLINEN YLIOPISTO**
Tuotantotalouden koulutusohjelma
**NURMI, ANSSI**: Liiketoimintamallit ja sovellukset mikro- ja desktoptehtaille
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Mikro- ja desktoptehtaat ovat pienikokoisia – usein pöydälle mahtuvia – tuotanto-, automaatio- ja työstölaitteita. Miniatyrisointi alkoi Japanissa 1990-luvun alussa. Pienten tuotantolaitteiden oletettiin säästävän resursseja pienten tuotteiden tuotannossa. 2000-luvulla useita pienikokoisia konsepteja on kehitetty ympäri maailmaa. Kaupallisten laitteiden ja sovellusten määrä on kuitenkin edelleen melko pieni. Tässä diplomityössä mikro- ja desktoptehtaiden käyttö analysoidaan sekä käyttäjien että laitetoimittajien näkökulmasta. Tutkimus sisältää kirjallisuuden lisäksi 18 teemahaastattelua.

Tutkimuksella ja teollisuudella vaikuttaa olevan erilainen näkökulman tuotantolaitteiden miniaturisointiin. Tutkimuksessa se linkittyy yleiseen filosofiaan tuotteiden ja tuotantolaitteiden koon yhteensovittamisesta. Teollisuudessa pieni koko on usein vain laitteiden toissijainen myyntiargumentti. Läpimurtoa hidastavat pienten osien ja esimerkkien puute, sekä tuotantoinsinöörien konservatiiviset asenteet. Teknologian kehitys vaikuttaa olevan vielä S-käyrän alussa. Teknologian kehitystä hidastavat systemaattinen kehitys ja markkinoiden hidas diffuusio. Tutkimuksen ja teollisuuden välillä tarvitaan edelleen kiineteää yhteistyötä. Laaja tuotantodemonstraatio on tarpeen.

Kirjallisuudessa on useita sovelluksia mikro- ja desktoptehtaille. MEMS tuotteita pidetään potentiaalisena sovellusalana, ja tutkimus tähtää usein täysautomaattisiin järjestelmiin. Teollisuudessa järjestelmiä käytetään puoliautomaattisena työkaluna lean kokoonpanossa ja komponenttivalmistuksessa. Tulevaisuudessa koulutus, prototuotanto toimistoissa ja laboratorioautomaatio ovat potentiaalisia sovelluksia. Tuotekustomointi myymälässä, laitteiden kotikäyttö ja MEMS toimiala sisältävät tiettyjä ongelmia. Laitetarjoajille teknologia tuo kaksi erinomaista asiakassegmenttiä (lean valmistajat ja täydet tehtaat), muutamia uusia asiakassegmenttejä (koulut, toimistot ja laboratoriot) ja se helpottaa jotain uusia liiketoimintamalleja (esim. alihankinta asiakkaan tiloissa).

# PREFACE

This thesis is a result of my work at Department of Production Engineering at Tampere University of Technology (TUT) in summer and autumn 2011. I worked for 7 months at TUT, researching the business aspects of micro and desktop production systems. Besides this thesis, I got to write two research papers relating to the topic. I’ve not been involved with the other TUT Microfactory projects. The background hopefully gives an external point of view and objectivity to the thesis.

In practise, I spend the first three months getting to know the literature and speaking with the people at TUT. Then, based on my own opinions and TUT’s networks, proper interviewees were chosen. I wanted to inverview both academics and the industry. During the interviews and I focused to build understanding about the topic. This report has been written based on the understanding, after the interviews.

I would like to thank my professors Reijo Tuokko and Petri Suomala. Your advices helped me a lot with the research process. In addition, I would like to thank Riku Heikkilä and the whole microfactory team. It was a pleasure to work with you. Finally, I would like to thank Matti Majuri and the whole team at K3111. I remember nice chats about corporate networks and microfactories. I hope it was beneficial for you too!

In addition, I would like to thank all the interviewees, providing valuable insight for the research: Mika Laitinen, Harri Heino, Seppo Kauppi, Tomi Pietari, Ilari Marstio, Timo Salmi, Eero Heurlin, Teemu Suominen, Jukka Kenttämies, Kalle Härkönen, Vesa Hirvonen, Jari Luotonen, Pekka Tirkkone, Cristoph Hanisch, Andy Zott, Andreas Hofmann, Phillipp Kobel, Alain Coroudrey and David Hériban.

Most importantly, this thesis is for my family and friends. You have supported me on everything I’ve done. I can’t thank you enough. I know, I’ve been a lot of away already, and I will be probably quite a lot abroad in the future as well. However, I’m never going to change. You are the most important thing I have.

Tampere 6.1.2012

Anssi Nurmi

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# ABBREVIATIONS AND NOTATIONS

| | |
|---|---|
| 5S | A housekeeping method in Lean production (sort, straighten, shine, standardize and sustain), see 'Lean' below |
| µ | Prefix of micro, "one millionth" |
| AG | Limited company (*Aktiengesellschaft*) [1] |
| B2B | Business to business |
| DOF | Degrees Of Freedom |
| EPFL | *École Polytechnique Fédérale de Lausanne* [2] |
| Co. | Company, used often with Japanese companies |
| i.e. | "That is" or "In other words" (*id est*) [3] |
| ibid. | Used to cite the preceding citation (*ibidem*) [3] |
| Inc. | Incorporation, used often with US companies |
| e.g. | "For example" (*exempli gratia*) [3] |
| et al. | "And others" (*et alii*) [3], used with citations having more than two authors |
| Fixed costs | Expences which are independent of production volumes |
| IRR | Internal Rate of Return (q.v. 4.2.3) |
| *Kanban* | A laminated signal card, by which pull-production is usually organized in Lean production, see 'Lean' below |
| KIT | Karlsruhe Institution of Technology |
| LCC | Life Cycle Costing |
| Lean | A production paradigm. To simplify, it is contradictory to traditional mass production. Personalized products are produced relative manually in small batches. (q.v. 3.2.3) |
| LSRO | *Laboratoire de Systèmes Robotiques*[2], a laboratory of EPFL |

| | |
|---|---|
| Oy | Limited company (*osakeyhtiö*) [4] |
| Oyj | Public limited company (*julkinen osakeyhtiö*) [4] |
| Macro | "Macroscopic" i.e. large, see "micro" |
| Marginal costs | Cost to produce a single additional product |
| MEMS | Micro Electro Mechanical Systems |
| Micro | "Microscopic" i.e. really small, "one millionth" as a prefix |
| N.B. | "To note", used to emphasize something (*nota bene*) [3] |
| NPV | Net present value (q.v. 4.2.1) |
| R&D | Research and Development |
| ROI | Return of Investment (q.v. 4.2.4) |
| SMED | Single Minute Exchange of Die, relates to Lean production |
| Tekes | The Finnish Funding Agency for Technology and Innovation (*Teknologian ja innovaatioiden kehittämiskeskus*) [4] |
| TUT | Tampere University of Technology |
| VTT | Technical Research Centre of Finland (*Valtion teknillinen tutkimuslaitos*) [4] |
| Write-off | Write-offs are used in accounting to divide a large cost into a long time scale |
| q.v. | Used to refer to other section of the thesis (*quod vide*) [3] |

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[1] German abbreviation
[2] French abbreviation
[3] Latin abbreviation
[4] Finnish abbreviation

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*Foreign words and mathematic variables are written in italic in this thesis.*

# 1. INTRODUCTION

Today's industrial production is rather different than a couple decades ago. Stevenson (2007) concludes that the industrial production begun in England in the 1770s with the industrial revolution. In the early days, skilled workmen produced low-volumes of unique products with simple and flexible tools. In 1911, Frederick Taylor introduced the Scientific Management (see Taylor, 1911). The industry started to produce products with interchangeable parts in precise division of labour. Low skilled workers were used to produce simple parts, the productivity of the industry exploded and the era of mass production began. Traditional mass production is based on economics of scale; the cost of a product decreases as production volumes increases. (Stevenson, 2007) The introduction of robotics and automation stepped up the efficiency of mass production.

Nowadays, the manufacturing industry is affected by e.g. extremely fast technology development, e-business, global competition and sustainable development. Consumers can deliver the products wherever they want which increases competition. Because of fast technology development and high rivalry, quality standards arise, products are becoming smaller, more complex and they have more variations. As a result, production has to adapt quickly to new product technologies and variations. The cost advantage of mass production disappears with a high rate of product variation. Consequently, new production paradigms for more flexible production have been introduced, e.g. Lean manufacturing. Because of ecologic and ethical issues, companies have to think more about energy consumption, use of recourses and recycling, among others.

In conclusion, manufacturing has nowadays many additional concerns, besides the economic objective to cut costs (Tuokko & Nurmi, 2011). New production technologies have been developed to support the new production paradigms, and to meet flexibility and environmental requirements of modern high-mix low-volume production. Miniaturization of production equipment has been suggested as one solution.

## 1.1. Micro and desktop production systems

In general, microfactory is an overall philosophy to minimize the production systems to meet the products in size (Heikkilä et al. 2007). Micro and desktop factory are the terms normally used to describe highly miniaturized manufacturing systems and equipment. However, the terminology alternates considerably. Terms used to describe highly miniaturized production equipment include: "desktop factory", "microfactory", "mini factory", "modular microfactory", "factory-in-a-suitcase", "palm-top factory" and "portable microfactory", among others. In addition, the definitions tend to vary.

The research of miniaturized production systems began in Japan in the beginning of 1990s. Research institutions, national universities and corporations developed smaller machines in order to produce micro parts and machines. Energy saving and economizing were some of the primary goals. (Okazaki et al., 2004)

In the late 1990's, the research spread around the world, and multiple miniaturized production systems were introduced. In addition new topics, such as modularity, virtual models and cleanrooms, embedded into the research. Under terms "microfactory" and "desktop factory", at least four types of concepts have been developed: microfactories as a set of small-size equipment, modular microfactory platforms, miniaturized machining units, and stand-alone robotic cells.

However, despite the vast global research efforts, the level of commercialization remains relative low, and the breakthrough remains unseen. So far, only few commercial desktop factories have been developed. The discipline lacks of empirical cases and industrial practice on microfactory-related business. This was the starting point for the latest microfactory project at TUT and for this thesis.

## 1.2. TUT DeskConcept project

Since 1999, miniature production systems have been one of the key research topics at Department of Production Engineering at Tampere University of Technology (TUT) (Tuokko, 2006). For more detailed description about the TUT microfactory research, please refer to the section 5.2, (Tuokko, 2006) and (Tuokko & Nurmi, 2011). DeskConcept is the latest microfactory project at TUT, being dated between September of 2009 and December of 2011. The project is funded by TUT and the Finnish Funding Agency for Technology and Innovation (Tekes). In addition, the steering group includes an interdisciplinary group of corporate partners: equipment providers, component providers and users or potential user of miniaturized automation. The five participating companies are Festo Oy, MAG Oy, Nokia Oyj, Vaisala Oyj and Wegera Oy.

The goal of the project is to study the economic and ecologic opportunities of the miniature production systems. There are two work packages. The first one includes evaluation of the economic and ecologic opportunities of micro and desktop factories. The second one includes building a roadmap, which evaluates how the Finnish industry can utilize and develop micro and desktop factory technology at the world class level. This thesis relates to both of the work packages.

## 1.3. Research question and objectives

The research question is phrased as following: How micro and desktop production systems can be used in the industry and how does it benefit the equipment providers, now and in the future? Respectively, there are four main objectives.

First of all, the author intends to bring a different point of view to the research. Secondly, the principal drivers to invest on miniature production systems should be discussed. Thirdly, potential applications for the technology should be revealed. In addition, the feasibility of the applications should be discussed; what might be reasonable now and what in the future. Fourth, business models for equipment providers should be discussed.

## 1.4. Standpoint

The research of the thesis lies between basic research and applied research. The project is conducted in co-operation with the university and companies. In addition, the objectives and the schedule of the thesis are predetermined. However, the goal of the thesis is to create common knowledge and to generate general principles and analysis.

The thesis has viewpoints of both users and providers of microfactories. In addition, the research touches both technical and business science. Relative topics of Industrial Engineering and Management are operations management (i.e. management of systems that create goods), technology management (e.g. dynamics of technology development) and marketing (e.g. analysis of buyer’s actions). In addition, management accounting is part of the analysis. It is presented in the chapter four. Because of the large amount of viewpoints, the thesis is divided into eleven chapters. The chapters 4, 7 and 8 are in the users’ point of view. The chapter 9 is in the equipment providers’ point of views.

## 1.5. Scope

In other occasions, micro and desktop factory might refer to e.g. 3D-printing (3D Systems Inc., 2011a) and infrastructure software (Rosenthal & Schmitz-Homberg, 2010). Within the manufacturing discipline, the prefix micro might refer either to micro-size manufacturing, small manufacturing equipment or both.

In this thesis, micro and desktop production systems refers to micro and desktop factories, as well as miniaturized production equipment in general, including e.g. machining units, stand-alone robotic cells, laboratory automation and rapid prototyping units. The equipment is mainly desktop-size. However, when compared to traditional machinery, small-size floor standing machines relate to similar benefits and business models than microfactories.

The thesis is mainly done for TUT, Tekes and the corporate partners involved in the project. However, the author believes also the whole microfactory discipline can benefit of it. According to the author’s understanding, the discipline has a shortage of similar business related research. In addition, the chapter 5 and the appendix 6 are fruitful sources of information of the equipment development within the discipline.

## 1.6. Structure

In chapter 2, the research method and material are discussed. The theoretical background of the thesis is presented in the chapters 3 and 4. Most importantly, they represent the viewpoints of the whole thesis. The chapter 3 focuses on the evolution of manufacturing industry and development of production technology. In addition, analysis of macro and micro environment is presented which will be applied for equipment providers. The chapter 4 focuses on investment in production equipment, in buyer's point of view. In chapter 5, the development and state of the art of micro and desktop production systems are introduced.

The chapters 6, 7, 8 and 9 are the primary results of the research. In chapter 6, nine industrial cases are presented. Eight of them are based on interviews. In chapter 7, the challenges and advantages of miniaturization are discussed. In chapter 8, possible applications for micro and desktop production systems are presented. In the end of the chapter, the roadmap estimates roughly the chronological order of feasible microfactory applications in the industry. In chapter 9, business models for equipment providers are discussed. The chapter 10 concludes the thesis. In chapter 11, the results are further discussed, and research recommendations are given.

# 2. RESEARCH METHOD AND MATERIAL

According to Saunders et al. (2008), research method is a combination of the techniques and procedures to obtain and analyse data. Research methodology instead, is a general theory on how research should be undertaken. The methodology includes multiple successive choices affecting to the whole research. (Saunders et al., 2008)

In this thesis, the declaration of research methods is even more important, in order to the reader can understand how the results and conclusions are created. This research is a mixed-method research, triangulation more precisely. It combines both literature and qualitative material of the interviews. The research is mostly exploratory and slightly predictive, latter relates to the roadmap in the section 8.6. The research methodology is a combination of pragmatism research philosophy, inductive approach, mixed-method procedure and a cross sectional time horizon. The terms are described more precisely in the next section.

In practise, the author became acquainted with the literature in the first place. Based on the literature, proper interviewees and questions for the interviews were chose. The interviews were recorded and transcribed afterwards. Finally the author focused to build understanding about the topic. The understanding developed incrementally during the research process. This report has been written based on the understanding, after the interviews.

## 2.1. Research method

The research methodology of this thesis is a combination of pragmatism research philosophy, inductive approach, mixed-method procedure and cross sectional time horizon. According to Saunders et al. (2009), pragmatism research philosophy adapts to the research question. Both observable objective phenomena and subjective meanings can provide acceptable knowledge for the research. The main focus is on practical applied research, to provide solutions for the research question. As a result, pragmatism research tends to combine both quantitative and qualitative data. (Saunders et al., 2009) In practise, this thesis accepted both literature and qualitative interviews as research material. Within the interviews, both facts and personal opinions were discussed.

Saunders et al. (2009) describe inductive approach as a mean to build theory. It is contradictory to deductive approach, which aims to test theory generated before. Gaining understanding of events, collection of qualitative data and a flexible structure are typical for inductive approach. (Saunders et al., 2009) The theory in the thesis is generated based on the interviews and the literature. In addition, Saunders et al. (2009) state that mixed-method procedure combines both quantitative and qualitative data in the analysis. Triangulation is a mixed-method procedure. It uses multiple data sources to provide collaborating research findings. (ibid.) In this thesis, the interviews are used to combine the applications and business models discussed in the literature. The interviews were used, because there is a clear lack of empirical cases and evidences in the literature. Finally, cross sectional time horizon refers to a particular moment. Longitudinal studies study phenomena over time.

## 2.2. Literature

The reference literature is based mainly on the conference proceedings (primary literature), as well as journals, magazines and books (secondary literature). In addition, few standards are cited in the thesis, relating to e.g. cleanrooms and TUT Microfactory. One can find publications, relating to micro and desktop production systems, in three different international microfactory conferences and in some general manufacturing conferences and journals (see below).

**International microfactory conferences:**

- IWMF International Workshop on Microfactories, since 1998
    - 1998, Tsukuba, Japan
    - 2000, Fribourg, Switzerland
    - 2002, Minneapolis, Minnesota, USA
    - 2004, Shanghai, China
    - 2006, Besançon, France
    - 2008, Evanston, IL, USA
    - 2010, Daejeon, Korea
    - 2012, Tampere, Finland
- IWMT International Workshop on Microfactory Technology
    - Annually in Korea 2005 – 2011
- DTF International Forum on Desktop Factory in SUWA
    - Annually in Japan since 2000

**Other conferences having relating publications, e.g.**

- IPAS International Precision Assembly Seminar
- ISAM International Symposium on Assembly and Manufacturing
- ICOMM International Congress on Micro Manufacturing
- 4M Conference on Multi-Material Micro Manufacture

**Journals having relating papers, e.g.**

- International Journal of Assembly Automation
- International Journal of Automation Technology
    - IJAT Vol.4 No.2 Mar. 2010 Special Issue on Microfactory

The three international microfactory conferences are IWMF International Workshop on Microfactories, IWMT International Workshop on Microfactory Technology and DTF International Forum on Desktop Factory. IWMF was the first international conference. It is held every other year in different locations. The next one will be held in Tampere, Finland in 18-20 of October of 2012. The DTF began in 2001. It is held annually in Japan by the DTF research consortium (see DTF, 2011). The IWMT began in 2005. It is held annually in Korea. However, the conference in 2011 was the last one until further notice. Other conferences, having relating publications, include IPAS, ISAM, ICOM and 4M. There are no primary microfactory journals. However, one can find relating papers in journals such as International Journal of Assembly Automation and International Journal of Automation Technology. The latter one has a Special Issue of Microfactory in IJAT Vol.4 No.2 Mar. 2010 (see Fuji Technology Press, 2010).

## 2.3. Interviews

Besides the literature, the research includes 18 semi-structured interviews (see appendix 5). The interviewees are both from academic and industry. The companies include equipment providers, component providers, users and potential users of miniature production systems. In addition, a production manager of one Finnish internet retailer, Verkkokauppa, was interviewed to find out about their product personalization processes. A member of Helsinki HackLab, a communal workshop in Finland, was interviewed to find out about their 3D printing projects and home fabrication aspects. The interviewee Kalle Härkönen and the company Biohit are listed both in the tables 2 and 4, because Biohit has an own stand-alone laboratory machine (q.v. 6.2.2). In addition, they are planning to use microfactories in the production (q.v. 6.3.3). Except the interview of Vesa Hirvonen at MAG, all the interviews are recorded.

Some new ideas came up in every single interview. Seven of them were extremely informative. In addition, the interviews have broadened author’s general point of view and understanding about the topic. The interviews are cited in the thesis. The chapter 6 and the sections 4.5, 5.4, 7.3, 8.5 and 9.1 are based primarily on the interviews. The rest of the thesis is mainly based on the literature, to avoid the reader’s misunderstanding.

# 3. EVOLUTION OF MANUFACTURING INDUSTRY AND PRODUCTION TECHNOLOGY

The theoretical background of the thesis is presented in the chapters 3 and 4. This chapter focuses on the evolution of manufacturing industry and development of production technology. As the industry is evolving, equipment providers have to monitor the business environment. Therefore, analysis of macro and micro environment are presented as well. The chapter 4 will focus on investment in production equipment.

In section 3.1 the major trends in the business of the 21th century are discussed. In section 3.2 the evolution of production paradigms is discussed. Three primary paradigms: craft production, Scientific Management and Lean management are presented to highlight the paradigm shift, and how it affects to production engineering. In section 3.3 the theory of technology evolution is discussed. Theory of the S-curve, technology diffusion, technological evolution and revolution are presented. In section 3.4, analysis of micro and microenvironment is discussed. Two famous tools, PESTEL analysis and the Porter's five forces analysis, are presented.

## 3.1. Major trends in the business of the 21$^{th}$ century

Stevenson (2007) states that there are numerous trends affecting the business in the 21$^{th}$ century, e.g. E-business and internet, management of technology, globalization, management of supply chains, outsourcing, agility and ethical issues. The management of technology refers both to product, process and information technology. (Stevenson, 2007) Emphasis on sustainable development includes the business ethics as well.

According to Himmanen (2007), the most significant global trends, affecting to Finnish industry, are 1. Innovation based competition, 2. Network organizations, 3. Growth of Asia, 4. The principle of absolute leadership and 5. The principle of selectivity. The first trend relates to the economist Xavier Sala-i-Martin's annotation. The competition advantage is based on three principles: produce cheaper products than competitors, provide better products with the same price or do something nobody else can copy. The fourth and fifth trend relates to wider trend of localization. (Himmanen, 2007)

According to Sipilä (2011), the CEO of JOT Automation, automation is becoming more demanding. Components and tolerances are becoming smaller, there are more product variants, product tracking is becoming more important, lead times are shorter as well as scalability is required for assembly and testing. In addition, the role of China is changing. Salaries are rising in China, products are becoming more complicated and quality demand is increasing, more training is required, human capacity is here and there fully used and Yuan is strong. As a result, there will be probably more automation in China as well. In addition, some of the production will shift to other low-cost countries and the production might even come back to Europe and USA. (Sipilä, 2011)

In author's point of view, the most significant trends supporting micro and desktop production systems are the emphasis on sustainable development and the tendency for agility. Presumably, smaller automation and production machines are supposed to save energy and resources, as well as enable flexible production.

## 3.2. Evolution of production paradigms

Production paradigm defines the principles, by which production is organized and managed. According to Stevenson (2007), mankind has been able to organize production since ancient times. The Egyptian pyramids, the Great Wall of China and the ships of the Roman and Spanish empires provide good examples. In the old days, production was mainly for public projects. However, production for sale and the modern factory system are based mainly on the Industrial Revolution. (Stevenson, 2007)

***Table 3.1.*** *The evolution of operations management (based on Stevenson, 2007, p.21)*

| Date | Contribution/Concept | Originator |
|---|---|---|
| 1776 | Division of Labour | Adam Smith |
| 1790 | Interchangeable parts | Eli Whitley |
| 1911 | Principles of Scientific Management | Frederick W. Taylor |
| 1911 | Motion study, use of industrial psychology | Frank and Lillian Gilbreth |
| 1912 | Chart for scheduling activities | Henry Gantt |
| 1913 | Moving assembly line | Henry Ford |
| 1915 | Mathematic model for inventory management | F.W. Harris |
| 1930 | Hawthorne studies on worker motivation | Elton Mayo |
| 1935 | Statistical procedures for sampling and quality control | H. F. Dodge, H. G. Romig, W. Shewhart, L. H .C. Tippettt |
| 1940 | Operations research applications in warfare | Operations research groups |
| 1947 | Linear programming | George Dantzig |
| 1951 | Commercial digital computers | Sperry Univac, IBM |
| 1950s | Automation | Numerous |
| 1960s | Extensive development of quantitative tools | Numerous |
| 1960s | Industrial dynamics | Jay Forrester |
| 1975 | Emphasis on manufacturing strategy | W. Skinner |
| 1975 | Emphasis on quality, flexibility, time-based competition, lean production | Japanese manufacturers, especially Toyota and Taiichi Ohno |
| 1990s | Internet, supply chain management | Numerous |
| 2000s | Applications service providers and outsourcing | Numerous |

Operations management is the management of a system or process creating goods and/or providing services (Stevenson, 2007). Operations management is based on the used production paradigm. There have been many new operations management principles, concepts and paradigm shifts both before and after the Industrial revolution. Table 3.1 provides a chronological summary of the evolution. In this chapter, three primary paradigms: craft production, Scientific Management and Lean management are presented to highlight the paradigm shift.

### 3.2.1. Expanded craft production after the Industrial Revolution

Stevenson (2007) defines craft production as a “system in which highly skilled workers use simple flexible tools to produce small quantities of customized goods”. The Industrial Revolution began in the 1770s in England, as new technical innovations, e.g. steam engine, enabled the combination of human and mechanical power. New iron machines were stronger and more durable than the simple wooden machines used before. More people moved into the cities and industrial production expanded. (Stevenson et al., 2007, p.21) Taylor (1911) argues that the operation principles were adapted directly from small workshops. A traditional factory at the time had e.g. between 500 and 1000 workers. The workers were divided into at least twenty or thirty trades, each of which was managed by foremen, previously top-class workers themselves. The production was divided between the trades, each conducting only a small phase of the work. (Taylor, 1911)

According to Stevenson (2007), craft production had some major shortcomings. First of all, the production was slow and costly, as talented employees had to custom fit all the parts into the products. In case of a breakdown, spare parts also had to be custom made. As a result, such production had no economies of scale. In other words, production costs did not decrease as the production volumes increased. (Stevenson, 2007) Womack et al. (1990) state that e.g. in the vehicle industry it was impossible to build two identical vehicles because the craft techniques caused variations. Because economies of scale did not exist, e.g. the vehicle industry had hundreds of small firms. (Womack et al. 1990) Taylor (1911) states that there were a few other concerns as well. First of all, there was no formal training. The working methods were handed down by word of mouth from one man to another, causing inevitable variations in the methods. Instead of one effective way, there were dozens of different ways to conduct any given piece of work. In addition, the system caused contradictory incentives for the workers. The management style is defined as “initiative and incentive”. (Taylor, 1911)

### 3.2.2. The ancestor of mass production – Scientific Management

American efficiency engineer Frederick Winslow Taylor introduced Scientific Management in 1911 in his monolog “The principles of Scientific Management”. Taylor (1911) states that the industry suffered from a lack of an analytic approach. Things were done as in the workshops in the early days, affecting both the motivation of employees and the efficiency of the factories. Scientific Management, or Task Management as he refers, divides manager's duties into four categories: developing a scientific method for each element of the work; scientifically selecting, training and teaching the workmen; cooperating with the workmen in order to ensure the scientific method is accepted; and the application of new incentive systems. As a result, the work was divided between planning and realization. Leaders should lead the factories instead of owners, engineers should design products and production instead of workers, and the foremen should optimize the working methods of the workers. The maximum output is achieved by work method standardization and performance-related incentive systems. (Taylor, 1911)

Stevenson (2007) states that the introduction of Scientific Management led to widespread changes in the manufacturing industry boosting efficiency to an entirely new level. Henry Ford was one of the first manufacturers in the USA to adapt successfully the principles of Scientific Management. In the first place, it was used to make the model T-Ford (see Figure 3.1) production more effective.  Mass production was accomplished by using low-skilled or semi-skilled workers with rather costly machines. Scientific Management lead to the use of interchangeable parts and a strict division of labour. However, an American inventor, Eli Whitley had already applied the concept of interchangeable parts for the assembly of muskets in 1790. The division of labour had already been introduced in 1776 by Adam Smith. (Stevenson, 2007)

According to Womack et al. (1990) the T-Ford was introduced in 1908. Within five years, the average task cycle in Ford's assembly plant was decreased from 514min to 1.19min, which had a huge impact on Ford's productivity. The key innovations were design for manufacturing, interchangeable parts, modern machine tools, strict gauging system and the moving assembly line. The vehicles, instead of the workers, moved around the assembly hall. By the early 1920s, the retail price of a model T-Ford was decreased by two-thirds. (Womack et al. 1990)

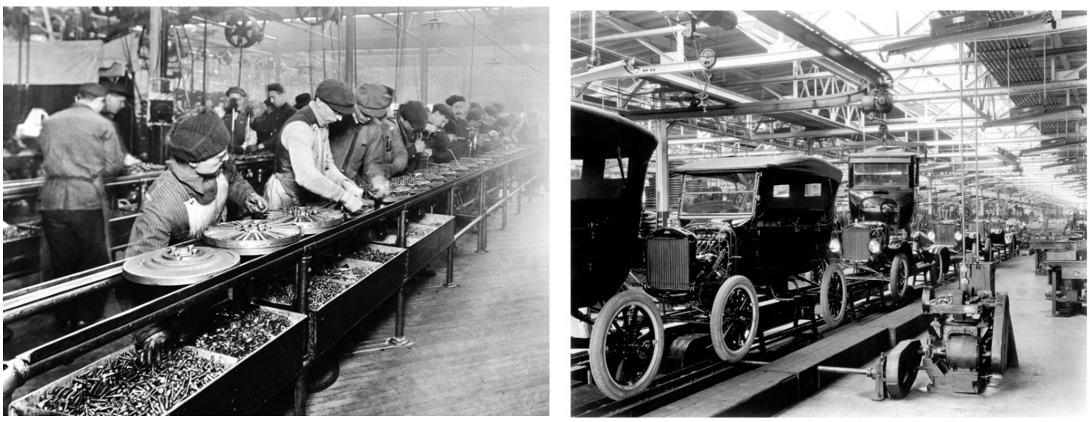

***Figure 3.1.*** *T-Ford production (Fung & Skillings, 2008)*

Stevenson (2007) states that all the results were not positive. For instance, it is argued that the methodology led to the abuse of the workers in the name of efficiency, as humans were treated as machines. In the early days, Scientific Management caused a lot of public outcry and Taylor had to stand up for his management principles. (Stevenson, 2007) By today's standards, Taylor's text seems bit harsh here and there. However, Taylor believed that employer, employees and customers could all gain from an effective production process (Taylor, 1911).

Besides the human factors, Scientific Management based mass production has some other shortcomings as well. Womack et al. (1990) describe that Ford had three vehicle models and three factories at the time. Each factory produced a single product. Cost advantages were achieved by huge volumes. Customers bought the vehicles because there were not many options in the market. By 1955, vehicle manufactures across the world became acquainted with the mass production principles. European and Japanese manufacturers provided cheap cars as well. In addition, the foreign cars included distinctive features. Export began and the American car manufactures couldn't adapt to the change and they lost sales. In fact, the market share of American car manufacturers has been decreasing ever since 1990. (Womack et al. 1990) In conclusion, mass production can provide huge cost advantages through economies of scale. However, extremely high production volumes are required and, therefore, it is not feasible to vary much the products.

### 3.2.3. New flexible production paradigm – Lean production

To simplify, Lean production is contradictory to traditional mass production. Personalized products are produced relative manually in small batches. It is effective because waste (e.g. overproduction, waiting and transportation) is minimized. Lean management is based on innovations among Japanese car manufacturers in the 1950s. In 1990, the term "Lean production" was taken up, and the principles were introduced to the general public in Western countries by the book "The Machine that Changed the World" (Womack et al. 1990). According to Hines et al. (2004), a lot of the work at Toyota was done under the leadership of Taiichi Ohno. In the beginning, the Lean principles were applied to engine manufacturing. In the 1960s, they were introduced to vehicle assembly and finally, in the 1970s, to the supply chain. In the last phase, the Lean principles were spread around Toyota's manufacturing network. (Hines et al., 2004)

Lean, or the Toyota Production System (TPS), is Toyota's general philosophy. Spear and Bowen (1999) emphasize, that Toyota has a concrete definition of an ideal production system. A customer should be able to walk into any of Toyota's factories and buy a customized and completely defect-free product; which would be produced at batch size of one, without wasting any resources or jeopardizing employees' safety. Any actions at Toyota are considered as temporary countermeasures, rather than solutions, in order to improve the system towards the ideal. Toyota does not consider the tools and practices as fundamental to TPS. (Spear and Bowen, 1999) However, the philosophy was divided into straight-forward rules and principles, when applied to Toyota's suppliers. These principles, defined in the following chapters, characterize current Lean production in Western countries (Hines et al., 2004).

Liker (2004) states that the TPS house (see Figure 3.2) was developed by Fujio Cho, a Japanese disciple of Taiichi Ohno, in order to present and teach Toyota Production System for the network of suppliers. In the house analogy, the roof of the house represents the goals: quality, costs, delivery, safety and morale. The outer pillars are Just-in-Time (JIT) production and *Jidoka*. Using smaller buffers, JIT reveals immediately the quality defects. According to *Jidoka*, the process should be stopped in case of any defects. In mass production, large buffers hide quality problems. In addition, there is no urgency to fix a problem as the production line keeps working with the buffers. In contrast, Lean induces urgency for every employee to fix problems, in order to keep the process running. Without buffers, the whole production stops in case of a failure. Therefore, all the employees have to fix the problem. In the centre of the system are people and waste reduction. The foundation is built out of various elements, including production levelling, standardized processes and visual management. (Liker, 2004) The TPS House was first published in Toyota's "blue book", a guidebook for Toyota's American suppliers. There are many variations of the house.

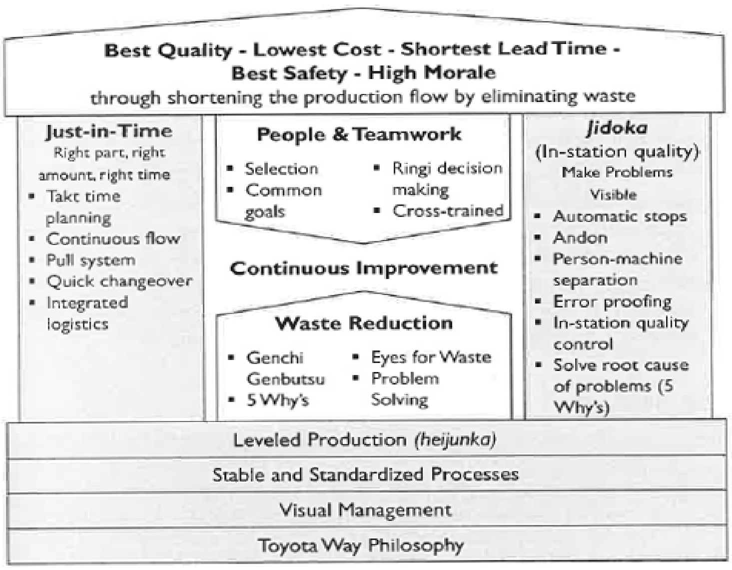


***Figure 3.2.*** *The Toyota Production System or the "TPS House" (Liker, 2004)*

The philosophy behind TPS is divided into 14 principles (Liker, 2004). Principles 9-14 relate mostly to leadership and organizational learning. The first eight principles, relating more directly to the production, are:

1. Management decisions should be based on long-term philosophy, even at the risk of short-term costs. However, the implementation should be rapid.

2. Create a constant flow to revel waste in the system. There are eight non-value-adding wastes in processes: overproduction, waiting, unnecessary transport, over-processing, excess inventory, unnecessary movement, defects and unused employee creativity. Business processes can include up to 90% of waste.
3. Use pull-production to avoid overproduction (*Kanban*).
4. Level production both by volumes and product variations (*Heijunka*). Orders in a period should be divided into identical product mixes produced each day. Traditional mass production minimizes the changes. For example, factory produces product A on Monday, Tuesday and Wednesday, product B on Thursday and products C and D on Friday. Lean, instead, prefers to produce relevant portion of all the products every day, providing more flexibility.
5. Create a culture to stop the process in the event of a problem and to fix the problems (*Jidoka*). In production, an operator pushes a special button (*andon)* when there is a problem. When the button is pushed, the leader has time to solve the problem until the car moves to the next step or the line stops automatically.
6. Standardize tasks. The standardized tasks are the base for continuous improvements and employee empowerment. Besides production tasks, any other tasks of the system, e.g. new product launch, can be standardized.
7. Use visual control to reveal problems in the systems. For example, the 5S waste elimination programs (sort, straighten, shine, standardize and sustain) include to the visual control. As production is clean, errors heave in sight.
8. Use only reliable and thoroughly tested technologies. The technologies have to support the employees, not the other way around. Fighting with unreliable systems is always complete waste.

Hines et al. (2004) summarize the Lean evolution in Western countries. In the 1990s, the first step involved the application of a set of tools and methods, e.g. *kanban* cards, 5S (housekeeping), SMED (changeover time reduction) and cellular manufacturing. The second step, 1990-1995, expanded lean thinking into the whole manufacturing process. At this step, companies tended to refer to Lean as only applying to limited islands on the shop-floor. The third stage, 1995-1999, expanded the Lean thinking into value streams. The application of *kaikuku* (i.e. improvements via breakthrough events), in addition to *kaizen* (i.e. continuous improvement), is a characteristic of the phase. The final phase, in the 2010s decade, involves extending Lean thinking into a much greater degree of contingency, reaching or even exceeding Toyota’s principles. The evolution of Western Lean relates to the implementation of Lean in companies. (Hines et al. 2004)

In addition, based on Lean, some new schools have been introduced, e.g. Agile production. Agile production differs slightly from Lean, emphasizing more e.g. variability, assembly-to-order systems and IT systems (Hines et al. 2004). However, the differences between the modern schools are minor in comparison to the difference between traditional mass production, or Scientific Management, and Lean management.

### 3.2.4. The paradigm shift for production engineering

Process equipment has been one of the least covered topics in the Lean literature (Shah & Ward, 2003, p.131). The book "Toyota Production System – Practical Approach to Production Management" by Yasuhiro Monden provides a good insight into how Toyota's production is organized in practise. Monden (1983) describes in detail e.g. the use of different *Kanban* cards, production planning procedures, the significance of lead times and setup times, layouts and job rotation of multi-function workers. In addition, formulas for cycle times and the amount of *Kanban* cards are presented (Monden, 1983)

It is clear that production engineering and machines have to adapt to the used production paradigm. It appears that Western companies tend to adapt primary only the Lean tools and method invented by Toyota (Hines et al. 2004). For the equipment provider or system integration, it does not matter whether or not the client's the production system extends to the full TPS philosophy. Instead, it is important to understand that Lean causes relatively different evaluation criteria and requirements (see Table 3.2) for production machines than it does for mass production.

***Table 3.2.*** *Some evaluation criteria and requirements for production machines with mass production and Lean*

| **Traditional mass production** | **Lean production** |
|---|---|
| • Automation is favoured | • Manual operations are favoured |
| • The reliability is important as the production volumes are usually huge<br>o However, there are safety stocks in case of breakdown | • Reliability is extremely important<br>o Lean tends to favour robust and thoroughly tested technologies<br>o In case of a breakdown<br>▪ There are no (or small) safety stocks<br>▪ *Jidoka* and *andon* stop the process for sure |
| • The setup time is not a major concern<br>o There are usually few changes<br>o Different products can be produced e.g. on different days | • Set-up time is extremely important<br>o *Heijunka* maximizes product variation in a day |
| • The machine is excellent, if<br>o Is has a large output<br>o It has 100% runtime | • Takt time is more important than output<br>o The output can be adjusted by<br>▪ Production levelling<br>▪ The amount of *Kanban* |
| • The cost of machines is compared directly to the costs of labour | • Improvements of manual operations have priority over investment in new machinery |
| • The process is based on automation | • Automation is seen as a tool for humans<br>o It is ideal to have many machines for one operator |

For example, with traditional mass production, the use of automation was justified by labour savings (Duncheon, 2002). According to Monden (1983), the goal of all the improvements in Toyota's production was to reduce the number of workers as well. However, improvements in machinery only complement improvements in manual operations. Toyota tends to improve the manual operations before getting new machines. New machinery may not pay off, if the number of workers can be reduced by improving manual operations. In addition, improvements to machinery often require standardizing manual operations as well. Robots, in particular, must remain as tools for men, not the other way around. (Monden, 1983)

## 3.3. Technology development

Technological evolution is the individual process, by which different technologies develop. It is estimated that, in the last 20 years, there has been more technological innovations than ever before in the human history. For consumers, the fast technological development can be both exciting and frustrating. For example, some people are waiting enthusiastically new technologies to show up. Instead, some would prefer not to learn new operation systems every other year. For companies instead, new technologies might provide opportunities as well as great challenges.

This section summarizes the dynamics of technology development. The S-curve, technology diffusion, technological evolution and revolution, the cyclic and systematic model of development, as well as classification of innovations are discussed. In the end of the chapter, the relation to production technology is discussed.

### 3.3.1. The S-Curve and technology diffusion

One of the main phenomena of the technology development is the S-curve, describing the phases of evolution of a technology. The measurement of development is linked to a certain performance parameter, e.g. processing speed or precision. In a graph, the increasing and descending performance curve reminds bit the letter S. The idea of S-curve was introduced by Devendra Sahal in the book "Patterns of technological innovations" in 1981. The life cycle consists of three main phases (see Figure 3.3, the blue line and the phases I-III). First, after the invention, it takes some time for the new technology to reach the market, as the customers and the developers are unaware of its benefits. Multiple competing technologies might exist on the market (I). Second, after the technology is established, the phase of incremental development starts. More and more developers work on the technology and it develops exponentially (II). Finally, technology reaches its limitation. The development slows down and saturates (III). (Shal, 1981) The life cycle can last from months (computer components) to centuries (magnetic compass), or anything between.

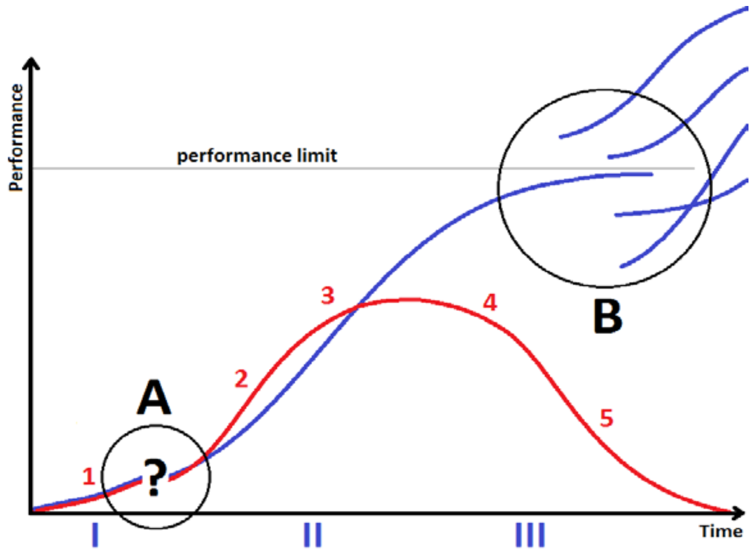


***Figure 3.3.*** *The S-curve of technology development*

The S-curve of technology development relates closely to technology diffusion, introduced by Everett Rogers in the book "Diffusion of Innovation" in 1962 (Rogers, 2003). The diffusion of a technology or an innovation includes five separate consumer groups (see Figure 3.3, the red line and the phases 1-5): innovators (1), early adapters (2), early majority (3), late majority (4) and laggards (5) (ibid.). Between the innovators and the early adapters, there is usually a "leap of fate" or "the chasm" (see Figure 3.3, A). The technology has to gather enough users, a critical mass, to enable the further development and technology diffusion.

Rogers (2003) states that there are five factors affecting to the speed of diffusion: relative advantage, compatibility, complexity, trialability or reversibility, and observability. Relative advantage describes the performance of new technology relating to the previous ones. Compatibility refers whether or not the technology is compatible with user expectations and complementary technologies. Complexity slows the diffusion as users have difficulties to understand the technology. Trialability and reversibility refer whether or not users can try the technology forehand or cancel the buying decision. Observability links to the fact, whether or not the advantages of new technology are easily perceived. Complexity slows the diffusion process, whereas all the other factors accelerate the diffusion. (Rogers, 2003)

Discontinuities are interesting and critical phases of technology development. Asthana (1995) states that as a result of a new technology, the performance jumps into a new S-curve. However, the performance can decrease momentarily as well, if the new technology has more potential to develop, e.g. introduction new lights (see Figure 3.3, B). (Asthana, 1995) Revolution occurs, if the new technology is considerably better and it replaces the old one. In general, market dynamics change as well. In the beginning, there might be variation between different type of technologies and approaches. As a result of competition, one technology will be usually selected. Consequently, all the developer focus on the dominant design and a new phase of exponential growth begins. For instance, Blue-ray followed DVD instead of HD DVD. However, Blue-ray has not replaced DVD yet, such as CD displaced C-cassettes and vinyl records.

One good example of the technology development is the Moore's law. According to the law, the amount of transistors on an integrated circuit doubles every 18 months. That is, the processing speed doubles every one and a half year and the technology develops exponentially. Incredibly, the law has held up for almost forty years. Gordon Moore (1965), one of the co-founders of Intel, actually predicted in the paper "Cramming more components onto integrated circuits" that the amount of transistor would double every year. The estimation was based on his professional experience and four points of quantitative data. At the time they were able to squeeze up 50 components into circuit and he predicted the number would increase up to 65,000 by 1975. (Moore, 1965) Moore argues that he never said the 18 months he gets always quoted for (Moore, 1975). However, the law is a good example of the S-curve. Recently there has been some discontinuity on the dynamics. Current processor technology might be at the end of its era. For more information about the Moore's law, please refer to (Intel Co., 2005)

### 3.3.2. Technology development within industries

The cyclical model of technology development was introduced by James Utterback in the book "Mastering the Dynamics of Innovation" in 1994. It relates directly to the S-curve. According to Utterback (1994) there are four phases in technology development (see Figure 3.4, the circle on the top): era of discontinuity, era of ferment, dominant design and era of incremental change.

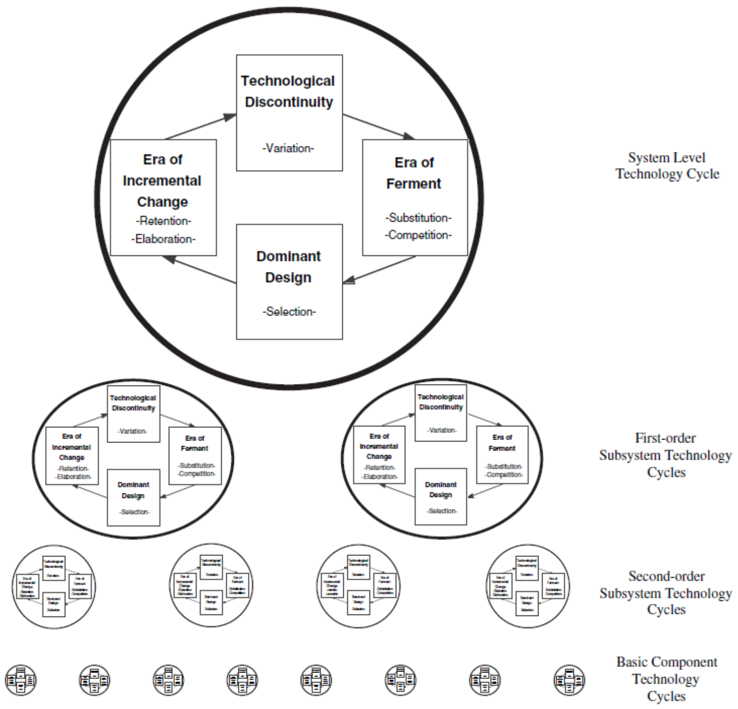


***Figure 3.4.*** *The systematic development of technologies (Murman & Frenken, 2006)*

The era of discontinuity is described in the previous chapter. A new technology is invented because of a performance upgrade (technology push, q.v. 3.3.3) or because of needs of a new market (market pull, q.v. 3.3.3). At the era of ferment, multiple concepts and realizations exist parallel. Some of the variants perform better and the technology development begins to stabilize towards one or few principal concepts. The era of ferment ends as new dominant design, one technological solution, is accomplished. Formats such as Mp3 and DVD are good examples of dominant designs. When the dominant design is set, the era of incremental change begins as more companies focus to develop the technology. (Utterback, 1994)

In addition, some technologies tend to develop as a sum of subsystems. Murman and Frenken (2006) state, that technologies usually include a hierarchical set of nested subsystems, each of which may include subsystems as well. Correspondingly, there are a system level, multiple subsystem levels and a basic component level. For example, an airplane includes e.g. wings, propelling device, and landing gear. A wing is a first-order subsystem and it contains e.g. flaps, fuel tanks and lights. Flaps are second-order subsystem and, respectively, they include steering flaps and breaking flaps. Similarly, the turning flaps are built from different components. (Murman & Frenken, 2006)

According to Murman and Frenken (2006), each technology level is developing based on the cyclical model. System level of technology develops as a sum of the subsystem developments. As a result, the development process is slower and more vicarious. The level of hierarchy (i.e. the number of subsystem layers) and homogeneity (i.e. the levels include technologies of similar complexity) affect to the development cycle as well. Standardizing core components and interfaces could help to fasten then development cycle. (Murman & Frenken, 2006) In conclusion, the uneven development of components affect to the development of the technology (Dedehayir & Mäkinen, 2008).

### 3.3.3. Classification of innovations

Innovations and technological developments can be classified with different frameworks. Henderson and Clark (1990), divides innovations into four groups according to the changes in the core concept and in the linkage between the components (see Figure 3.5). Incremental innovations represent the smallest change. The linkage between the components remains the same and the core concepts are reinforced. Slightly larger change is achieved by modular innovation or architectural innovation. In the former, the linkage remains the same but the core components are completely overturned. In the latter instead, the core concepts improve slightly or remains the same, but the construction or linkage between parts changes dramatically. Radical innovation changes both the structure and the core concepts. (Henderson & Clark, 1990)

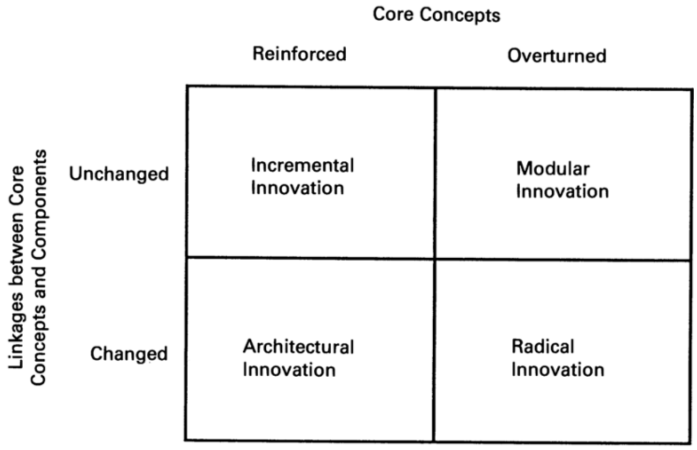


***Figure 3.5.*** *Classification of innovations (Henderson & Clark, 1990)*

Henderson and Clark (1990) present an example of room air fan with an electronic motor and blades. Improvements on motor or blade design would be incremental. Introduction of a portable fan would be an architectural innovation. Development of a new kind of motor would be modular innovation. Introduction of central air system would be radical innovation instead. (Henderson & Clark, 1990) All of the processes include in the development of technologies in a given industry. However, in some industries the development can be characterized e.g. by modular innovations.

### 3.3.4. Market pull vs. technology push

According to one school, there are two different kind of technology development: market pull and technology push. With the market pull, the main concern is to fulfil customer needs and requirements. Technology is developed for the needs. As a result, the technology develops mainly incrementally. With the technology push, the main concern is to increase performance of the technology. The development requires more recourses but it enables more radical developments. Technology push is common with new and fast developing technologies.

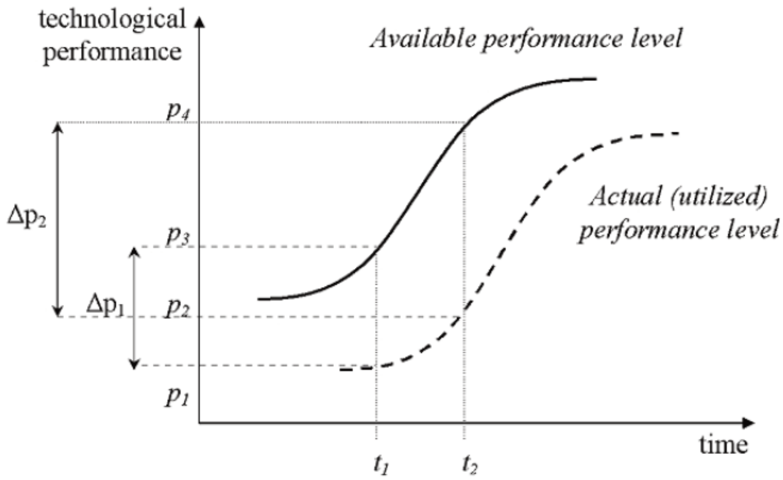


***Figure 3.6.*** *Technology development and its utilization (Dedehayir & Mäkinen, 2008)*

In addition, there might be a chronological gap between technology development and utilization, especially in technology driven industries. Dedehayir and Mäkinen (2008) suggested a way to measure the performance-gap between the S-curves of technology development and technology utilization (see Figure 3.6). In their study, a clear technological co-evolution between the CPU (central processing unit of a computer) development and PC games' CPU requirements was demonstrated. It appears that, to guarantee the success, the game developers may tend to launch the products focusing to completely other factors than the technical performance. Therefore, the technological development is not the bottleneck factor. (Dedehayir & Mäkinen, 2008)

### 3.3.5. Evolution of production technology

Evolution of production technology is characterized by the systematic development. New production equipment and machines, e.g. robots, conveyors and production lines, are built out of subsystems. The subsystems, e.g. axes, motors and control units, are based on lower level subsystems and components. The development of components, e.g. bearings, coils and hydraulic components, affect to the development of the equipment. The question, whether or not there is performance gap between the equipment performance and the production process requirements, requires more research in detail.

It appears that micro and desktop production systems lie in the "chasm", in the early stage of the S-curve, between early adaptors and early majority in the market. The development process has been characterized by technology push. The development began in research centres and companies before the customers required such small production systems. The offering of small components is stated as one of the main preventing factors to the development (e.g. Heikkilä et al., 2010). Therefore, a lot of subsystem development is required before system development is possible. In addition, production technology appears to have quite long technology diffusion. For example it took 12 years for automation to really take off, after the key technologies were invented.

## 3.4. Analysis of micro and macro environments

Microenvironment includes companies' direct interest groups, e.g. customers, competitors and investors. Macroenvironmet includes, in addition, other factors affecting to the interest groups and business environment. Both mico and macroenvironment cause threats and possibilities for a company or for an industry.

In this section, two tools, the Porter's five forces analysis and PESTEL analysis, are presented. It should be emphasized that neither of the tools provide exact analysis or answers. The Porter's five forces analysis describes some guidelines for strategic planning as well (Porter, 2008), but PESTEL is more a checklist type of tools to identify significant factors in surroundings. The analysis will be implemented for the industry of micro and desktop production systems in the section 9.6.

### 3.4.1. Porter's five forces – analysis of microenvironment

Porter's five forces analysis is a tool to analyse microenvironment of a given industry. Michael Porter presented the ground breaking model in his article "How competitive forces shape strategy" in 1979. Porter describes that, in addition to the rivalry with the direct competitors, there are four additional forces affecting to the profitability of an industry (see Figure 3.7): bargaining power of suppliers, bargaining power of customers, threat of substituting products and threat of new entries (Porter, 1979).

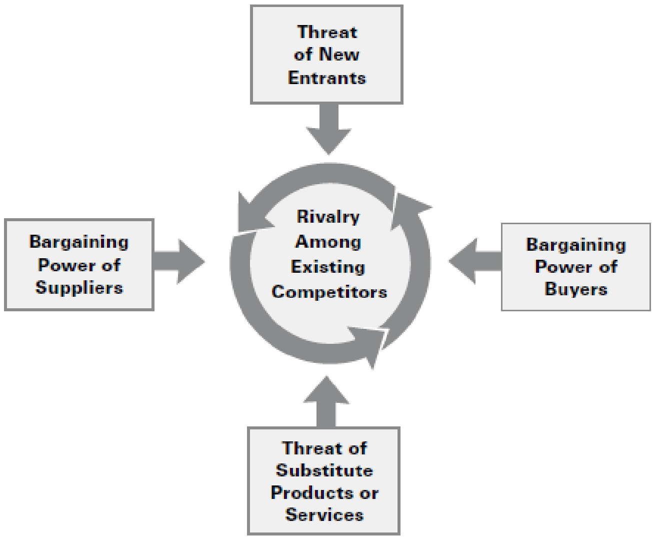


***Figure 3.7.*** *Porter five forces analysis (Porter, 2008)*

According to Porter (2008), there are several factors boosting or diminishing the forces. The barriers of entry prevent new companies to enter into industry. They are therefore positive for the companies already in the industry. The major barriers are supply-side economies of scale (i.e. classical economics of scale), demand-side economies of scale (e.g. it is convenient for the customer to use Windows as everybody do, because there are many programs), customer switching costs (e.g. mobile phone contracts), capital requirements (i.e. it is expensive to enter the business), incumbency advantages independent of size (e.g. company already on the market has the best geographical locations), unequal access to distribution channels (e.g. entrance to supermarkets for new foods) and restrictive government policy (e.g. alcohol monopoly in Finland). (Porter, 2008)

Porter (2008) states that strong bargaining power of customers or suppliers can cut the profits of the whole industry. Suppliers have strong bargaining power if there is a low amount of suppliers (e.g. Microsoft for PC providers), the industry is not important for the suppliers. In addition, increasing factors include supplier switching costs (e.g. Boeing and Airbus for airlines), suppliers' differentiated products (e.g. patented drugs), a lack of substitutes for the supplier product (e.g. pilots unions for airlines) or possibility to integrate forward (i.e. to enter directly into the industry). (ibid.)

Instead, Porter (2008) states that the customers have a lot of bargaining power if there are few customers (e.g. operators to mobile phone providers), the products are standardized, customers have small switching costs or the customers can integrate backwards (i.e. buy the products from the suppliers). The customers are usually price sensitive if they earn only small profits, the quality of customers' product is little affected by the industry's product (e.g. photographers buy expensive cameras because the quality is important for them) or the product has small impact on customers' other costs (i.e. buyer can focus on price). (ibid.)

Porter (2008) states that the rivalry within industry includes e.g. price competition, new product introductions and advertising campaigns. The factors increasing the rivalry are a high amount of competitors all being roughly equal (i.e. all tend to steal customers from each other), slow industry growth (causing fierce fight over market shares), high exit barriers (e.g. costly factories), rivals' aspiration for leadership (causing excess), firms' inability to read each other's signals (e.g. no one tries different approaches), high fixed costs combined to low marginal costs (e.g. in paper and aluminium industry companies tend to cut the prices even near to marginal costs to cover the fixed costs), expansion of capital in large investments (disturbing the supply-demand balance) and perishable products (i.e. firms cut the price while the product has still value). (ibid.)

Porter (2008) describes substitute as a product providing similar function than the product, e.g. email to post, videoconference to travelling and plastic to aluminium. The threat of the substitutes is high if the substitute provides good price-performance ratio compared to the product (e.g. telephone calls vs. Skype) or if the buyers switching costs are low (e.g. changing a brand of a drug). (ibid.)

### 3.4.2. PESTEL analysis of macroenvironment

The PESTEL analysis is a variation of multiple abbreviations, referring to similar topics. The letters in PESTEL refer to political, economic, social, technological, ecologic and legal. Gillespie (2009) describes, that the changes affecting to companies in the microenvironment includes e.g. tax changes, new laws and demographic change. There are multiple variations of the same framework, all emphasizing bit different factors. There are e.g. STEP, PESTEL, PESTLE, PESTE, PESTLIED, SLEPT and STEEPLE, among others. In addition, the STEEP used for sustainable development (Gillespie, 2009) PESTEL is discussed here, because it was one of the first ones and most commonly used frameworks of macroenvironment. Table 3.3 provides a summary of the different factors, affecting to the macroenvironment.

***Table 3.3.*** *Different factors in PESTEL analysis (based on Gillespie, 2009)*

| | **LOCAL** | **NATIONAL** | **GLOBAL** |
|---|---|---|---|
| **Political** | Provision of services by local council | National government policy on subsidies | World trade agreements e.g. further expansion of the EU |
| **Economic** | Local income | National interest rates | Overseas economic growth |
| **Social** | Local population growth | Demographic change (e.g. ageing population) | Migration flows |
| **Technological** | Improvements in local technologies e.g. availability of Digital TV | National wide technology e.g. online services | International technological breakthroughs e.g. internet |
| **Environmental** | Local waste issues | National weather | Global climate change |
| **Legal** | Local licences/planning permission | National law | International agreements on human rights or environmental policy |

According to Gillespie (2009), political factors refer to governmental decision, affecting to education, infrastructure and subsidization of certain industries or production of certain products. Economic factors include e.g. interest rates, taxation changes and economic growth. For example, high interest rates favour investments. Social factors include e.g. the ageing of population and other demographical changes. For example, the ageing of population has affected to the availability of workforce, increased the demand for medicines and decreased demand for toys instead. (Gillespie, 2009)

Gillespie (2009) states that the technological factors refer to technological changes (discussed in the section 3.3). Technological factors can e.g. cut costs, improve product quality and lead to innovations. Environmental factors include changes in weather and climate. For example, the concern of global warming has stiffened legislation and increased taxes of fuels. Companies have to emphasize more on environmental issues. Legal factors refer to the legislation in the environment in which firms operate. Legislation affect e.g. to recycling, corporate responsibility and the availability of workforce, by the laws of minimum salaries and discrimination. (Gillespie, 2009)

# 4. INVESTMENT IN PRODUCTION EQUIPMENT

This chapter discusses purchase of B2B products and evaluation of investments in production equipment. Each company has certain methods to estimate investments. The methods vary from occasion to occasion depending on the industry, company and scale of an investment. For the equipment providers, in order to sell their products, it is vital to understand how the manufacturers evaluate the purchases.

Investment is "an asset or item that is purchased with the hope that it will generate income or appreciate in the future" (Investopedia, 2011). According to Neilimo and Uusi-Rauva (2001), the main difference between an investment and a cost is the time which involves risk. Investments are divided between financing and real investments. The former includes e.g. investments in bonds and debentures. The latter includes investments on various factors of production, e.g. buildings, machines or marketing campaigns. (Neilimo & Uusi-Rauva, 2001) This chapter focuses on real investments, relating to production equipment.

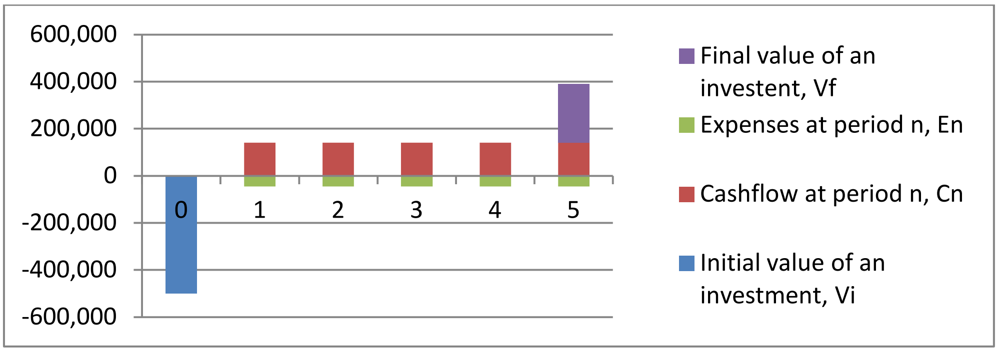


***Figure 4.1.*** *A simplification of life cycle costs and returns of an investment*

In the first place, company has a certain need to purchase equipment. The requirements and different options are discussed in the section 4.1. The dilemma of an investment in equipment is summarized in the Figure 4.1. An investment has certain initial expenses, expected cash flow and expenses in the future, as well as an expected residual value. Managers have to evaluate, whether the investment is profitable or not, and how it relates to other options. Calculation methods are discussed in the section 4.2. However, future values are always forecasts with uncertainty. In addition, there are many factors, e.g. quality, robustness and aftersales, which are difficult to quantize. Few other factors relating to B2B purchases are discussed in the section 4.3. An example of an investment in production equipment is presented in the section 4.4. The section 4.5 summarizes observations of the interviews.

## 4.1. Background of an investment in equipment

Usually, investment in production equipment is based on the needs of the production system. More precisely, equipment is bought if the production system requires general upgrades, more capacity and/or new process. More capacity is needed if the demand exceeds or, according to forecasts, will exceed too much the current capacity. New processes might be required to produce new products or e.g. to improve quality of the current products. The general improvements of the production systems include e.g. flexibility improvements and bottle neck elimination.

According to Stevenson (2007), capacity requirements should be based on forecasts of future demand. Both quantity of demand in a given period and more precise timing should be forecasted. According to the forecast, required changes of the capacity (increase, decrease or no changes) can be estimated. The forecasts can be divided into long-term and short-term forecasts. The former refers to the level of capacity and how it evolves, e.g. growth, declining or cyclical waveform. The latter refers to the variations in a short period of time. In addition, there are irregular variations, relating to e.g. breakdowns and external factors, which are impossible to forecast. The timeframes vary to a great extent from industry and industry. (Stevenson, 2007)

### 4.1.1. Capacity requirement evaluation

Stevenson (2007) describes that a rough estimate of capacity can be estimated based on forecasted annual demand. For example, products A and B have annual demands of 400 and 300 units. The processing times for a given machine are 5h and 8h respectively. The products require thus 4,400 machine hours in a year. If the machine runs for 8 hours in a day 250 days in a year, the capacity is 2,000 hours per year. Therefore, 4,400/2,000 = 2.2 (3) machines are required. (Stevenson, 2007)

Profitability can be roughly estimated with cost-volume analysis. Stevenson (2007) describe that the cost-volume analysis estimates the income of a company under different operating conditions. The analysis is based on fixed and variable costs (see Figure 4.2, the graph on the left). Fixed costs (e.g. rents, heating and salaries of business administration) do not change along with production volumes. Instead, variable costs (e.g. material, energy and salaries of employees) change along with volumes. Total cost is the sum of fixed and variable cost. Total revenue is the cumulative selling price of all products. In the break-even point, cost equals revenues (see Figure 4.2, the graph in the middle). (Stevenson, 2007) However, in the long-term, all costs are variable.

| | |
|---|---|
| FC | Fixed cost |
| VC | Variable cost |
| TC | Total cost (FC + VC) |
| TR | Total revenue |
| BEP | Break-even point (where TC = TR) |

Stevenson (2007) states that capacity expansion might involve step costs. For example, machines have always limited capacity. If the capacity runs out, a new machine has to be bought. As a result, both capacity and the fixed costs increase step by step. The total cost curve is therefore saw-edged and multiple break-even points can exist (see Figure 4.2, the graph on the right). Most importantly, there might be no break-even point in a given volume range. (Stevenson, 2007) Here the company would lose always money by using a single machine, even with the full capacity.

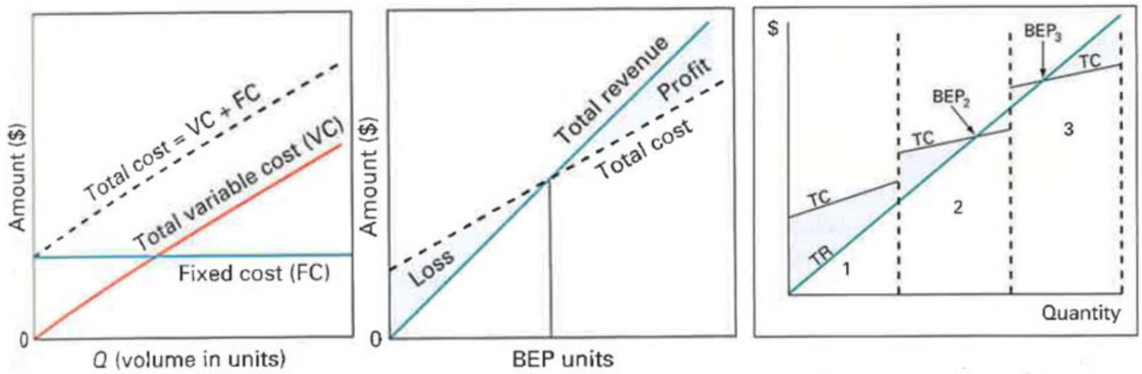


***Figure 4.2.*** *Accumulation of fixed, variable and total costs; Profits, losses and the break-even point; Multiple brake-even points (adapted from Stevenson, 2007)*

Besides the fact that all costs are variable in the long-term, the cost-volume analysis has another critical shortcoming. In reality, total costs do not increase linearly. Because of economies and diseconomies of scale, the average cost to produce a single product (AC) first decreases and then starts to increases as the production volumes increase (see Figure 4.3). Marginal cost (MC) refers to the cost to produce a single additional product. In the most profitable production volume, the average cost equals to marginal cost (Neilimo & Uusi-Rauva, 2011). Economies of scale are caused by the fact that the fixed costs are divided between more units, construction costs decrease and operations become more standardized and thus more effective. Diseconomies of scale occur because distribution costs increase, complexity increases, inflexibility causes problems and larger production leads usually to heavy bureaucracy (Stevenson, 2007).

| | |
|---|---|
| AC | Average cost |
| MC | Marginal cost |

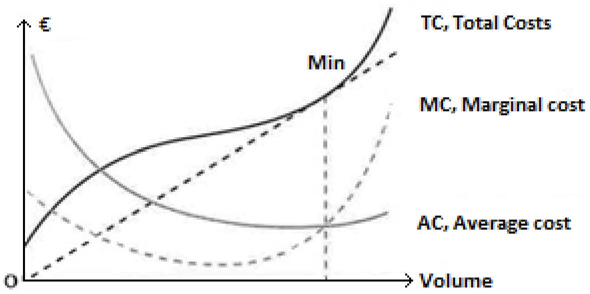


***Figure 4.3.*** *Cost curves (adapted from Neilimo & Uusi-Rauva, 2001)*

In addition, the price elasticity of demand defines both the most profitable price for a product and production volumes (Pekkarinen & Sutela, 2007). However, the cost-volume analysis is a practical tool to evaluate roughly e.g. how many products should be sold to break even a machine, how much a certain production volume profits a company, or whether or not the fixed costs can be covered only by the capacity.

### 4.1.2. Alternatives for an investment in production equipment

There are few alternatives to enhance capacity, in addition to equipment purchases. According to Stevenson (2007), companies can outsource (i.e. buy) the required factors of production, or enhance the efficiency of production. The decision to outsource includes certain factors to be considered (see Table 4.1). First of all, production of a given product or service might be cheaper in-house if the required capacity, skills and time exist. Outsourcing, on the other hand, can be feasible if there is a lack of capacity and expertise. Gaining more in-house capacity includes step costs and can lead to overcapacity. If the production volumes are large and the demand is stable, the company is usually better off by producing itself. Instead, suppliers usually have orders from multiple sources, and the fluctuation tends to offset. (Stevenson, 2007)

***Table 4.1.*** *Make-or-buy decision (based on Stevenson, 2007)*

| | **Advantage** | **Disadvantage** |
|---|---|---|
| **Make**<br>• Production with current capacity<br>• Purchase of machines<br>• Leasing of machines<br>• Overwork | • Cost savings (if required capacity and skills exist)<br>• Flexibility<br>• Quality monitoring<br>• Learning curve | • Additional fixed costs (e.g. of bureaucracy and management)<br>• Costs of overcapacity (step costs)<br>• High average costs in the beginning (learning curve) |
| **Buy**<br>• Outsourcing | • Cost savings<br>• Possible quality enhancing<br>• Additional expertise | • Additional fixed costs (e.g. of transportation)<br>• Information management<br>• Lost control over operations<br>• Quality monitoring |

However, outsourcing includes downsides as well. Stevenson (2007) describe, that outsourcing can cause additional fixed costs, e.g. of transportation. In addition, outsourcing includes risks, e.g. risk of data leakage and loosing control over production. Quality is a two-sided question. On the one hand, a supplier might have additional expertise enhancing the quality. On the other hand, a company loses the ability to monitor the quality precisely. In addition, there are several actions to enhance the capacity with current machines. Companies can e.g. make the system more flexible, remove bottlenecks and attempt to smooth capacity requirements (Stevenson, 2007) Companies can also overwork the employees or e.g. work in two shifts.

## 4.2. Investment calculations

According to Neilimo and Uusi-Rauva (2001), investment calculations are based on the scarcity of recourses. The calculations aim to direct the scarce recourses to the most profitable option. The term life cycle costing (LCC) relates closely to investments. LCC takes into account the costs and returns of given object during the whole life cycle, e.g. purchase costs and operating costs, including costs of maintenance, upgrading, education among others. For example, the general purchase costs, e.g. planning, estimation and lost labor capacity, count typically 10-15% of the purchase price. There are five common methods to calculate the investments: present value method, equivalent annuity method, internal rate of return method, return on invested capital and payback method. The three former are dead reckoning methods and the two latter are simplified methods. (Neilimo & Uusi-Rauva, 2001)

All the methods are based on the same starting values. According to Neilimo and Uusi-Rauva (2001), the initial value of an investment ($V_i$) is the basic cost relative close to the decision making. There are no great risks involved. However, there is the problem of scope (life cycle costing), described above. The length of an investment period ($t$) is an integer, indicating the amount of time periods, e.g. years or month, in the investment's life cycle. In a given period $n$, there will be a certain cash flow ($C_n$) and expenses ($E_n$). In the end, the investment has a final value ($V_f$). (Neilimo & Uusi-Rauva, 2001) With production equipment, $V_f$ is usually small. In general, the final value might be positive (i.e. company can sell the old equipment), zero (i.e. the equipment is totally useless and has no value) or negative (e.g. the company has to use money to dispose and/or recycle the equipment). The cash flow is estimated based on expected sales and prices, and the expenses are counted based on the required capacity.

| | |
|---|---|
| $V_i$ | The initial value of an investment |
| $t$ | Time of the investment (the amount of time periods) |
| $C_n$ | Cashflow during the period $n$ |
| $E_n$ | Expenses during the period $n$ |
| $V_f$ | The final value of an investment |

According to finance theory, the same amount of money has different values now than in the future. Neilimo and Uusi-Rauva (2001) define interest as compensation for usage of money. Discounting is used to compare sums of different periods of time. For example, it is more valuable to have a bill of ten euros today than next year. One can invest the bill now and earn interests before the next year. Discounting is therefore a reverse operation to interest calculations. The base of discounting is the discount rate $i$. It is the interest rate, which could be earned with an investment of similar risk in the financial market. For example, low-risk government bonds have usually a nominal interest rate of 10%. (Neilimo & Uusi-Rauva, 2001)

| | |
|---|---|
| $i$ | Discount rate, nominal interest rate (e.g. 10%, $i$=0.10) |
| $j$ | The rate of inflation (e.g. 2%, $j$=0.02) |
| $i_r$ | Real interest rate (based on $i$ and $j$, e.g. $i_r$=0.078) |

The present value ($V_p$) of a future value ($V_f$) can be calculated with the formula (1). For example, if a risk-free interest rate is 10%, it is as valuable to have 10€*(1/1.1) = 9.09€ today than a bill of ten euros after one year. However, also inflation $j$ effects to discounting. The real interest rate $i_r$ can be calculated with the formula (2). For example, with an inflation of 2%, a risk-free interest rate 10% corresponds to a real interest rate of 7.8%. A bill of ten euros in the next year would have an equivalent value of 9.30€ today. It is slightly more than in the first case, because the real interest rate is lower. Inflation cuts some of the potential interest profits.

$$V_f = V_f \frac{1}{(1+i)^n} \tag{1}$$

$$i_r = \frac{i-j}{1-j} \tag{2}$$

### 4.2.1. Present value method

With present value method, all the returns and costs caused by an investment, are discounted to present moment and summed together. Combined to a proper discount rate, the investment is profitable if the total sum is positive. The largest net present value refers to the best investment between different options. If the sum were zero, the company would gain equal profit with an equal risk in the financial market. The investment is therefore not financially profitable. The net present value (*NPV)* can be calculated with the formula (3). (Neilimo & Uusi-Rauva, 2001) In Excell, the net present values of returns and costs can be counted by the PV-function.

$$NPV = V_i - \sum_{n=1}^{t} \frac{C_n - E_n}{(1+i_r)^n} + \frac{V_f}{(1+i_r)^t} \tag{3}$$

### 4.2.2. Equivalent annuity method

Equivalent annuity method is a reverse calculation method to the present value method. The initial investment is divided between investment periods. If the annual returns are greater than annual costs, the investment is profitable. Because of discounting, the initial investment can’t simply be divided by the amount of time periods. In addition, the final value of an investment ($V_f$) has to be discounted and added to the initial value ($V_i$). The annual capital costs, annuities, can be calculated with the formula (4). (Neilimo & Uusi-Rauva, 2001) In Excell, the annuities can be counted separately with the PMT-function.

$$A = (V_i + V_f \frac{1}{(1+i)^n}) * \frac{i_r(1+i_r)^t}{(1+i_r)^t - 1} \tag{4}$$

### 4.2.3. Internal rate of return, IRR

Internal rate of return method estimates the interest rate, by which the net present value equals zero. Investment is profitable if the interest rate is greater than the eligible discount rate or yield requirement. According to Neilimo and Uusi-Rauva (2001), the yield requirement depends on the type of an investment. There is usually no yield requirement for obligatory investments, e.g. investments relating to legal work safety. Instead, the return requirement might be e.g. 6% for actions protecting the company's position in the market, 12% for renovating of machines, 15% for investments aiming to reduce costs, 20% for investments aiming to increase profits and 25% for risky investments to acquire new markets. (Neilimo & Uusi-Rauva, 2001)

Internal rate of return (*IRR*) can be estimated by dividing initial investment ($V_i$) by annual profit ($C_n – E_n$). The final value of an investment ($V_f$) has to be combined to the annual returns. The result is compared to tables, having different *IIR* values for different investment lengths. (Neilimo & Uusi-Rauva, 2001) In Excell, the *IRR* can be calculated directly with the RATE-function.

### 4.2.4. Return on invested capital method, ROI

Return on invested capital method is a simplified version of the internal rate of return method. Return on investment (*ROI*) can be used to evaluate the investment in the same way as the internal rate of return (*IRR*). *ROI* can be calculated with the formula (5). Instead of discounting, *ROI* divides the typical annual net profit ($P_a$) by average investment ($V_a$). To compensate the discounting, write-offs can be used to calculate the annual net profits. (Neilimo & Uusi-Rauva, 2001)

$$ROI = \frac{P_a}{V_a},\ P_a = C_a - W, V_a = \frac{V_i - V_f}{t} \qquad (5)$$

### 4.2.5. Payback method

Payback method defines the time period, after which the cumulative profits of investment exceed the initial investment. If the annual cash flow (*C*) and the annual expenses (*E*) are expected to be constant, the payback time (*T*) can be calculated with the formula (6). It is a simple method to evaluate the profitability of investments. The best investment has the shortest payback time. Downside of the method is the exclusion of interest. However, it is easy and illustrative, and thus commonly in use. A more precise payback time can be calculated iteratively by discounting and summing profits separately. After the payback time, profits exceed the initial investment. The payback method highlights investment's funding effect instead of profitability. (Neilimo & Uusi-Rauva, 2001)

$$T = \frac{C - E}{V_i} \qquad (7)$$

### 4.2.6. Sensitivity analysis

According to Neilimo and Uusi-Rauva (2001), uncertainty and risks relate always to investments. The calculations are always based on uncertain values, estimations and forecasts. Risk is defined as measurable uncertainty. Risk includes both information about possible events and their possibilities respectively. Uncertainty is used, when one knows that something might happen but the possibility is unknown. The sensitivity analysis is usually the first step in order to analyse the uncertainty relating to an investment. (Neilimo & Uusi-Rauva, 2001)

With the sensitivity analysis, the profitability of an investment is calculated by changing one or multiple elements relating to the investment. After every change, the impact to the profitability is analysed. After analysing every single element, one knows better which elements have a large impact on the profitability and which elements are not that critical. As a result, the critical elements can be further analysed. (Neilimo & Uusi-Rauva, 2001)

### 4.2.7. The use of the investment calculation methods in the industry

Neilimo and Uusi-Rauva (2001) state that the use of different investment calculation methods was analyses in a research of fifty largest Finnish corporation and their business units (see Table 4.2).

***Table 4.2.*** *Investment calculation methods used by the business units (adapted from Neilimo & Uusi-Rauva, 2001, p.201)*

| | **Applied in general** | | **Used as principal method** | |
|---|---|---|---|---|
| **Method** | **Business units** | **%** | **Business units** | **%** |
| Present value method | 14 | 35.1 | 1 | 2.5 |
| Equivalent annuity method | 6 | 15.0 | 0 | 0 |
| Internal rate of return, IRR | 36 | 90.0 | 23 | 57.5 |
| Return on invested capital, ROI | 17 | 42.5 | 4 | 10.0 |
| Payback method | 36 | 90.0 | 12 | 30.0 |
| Other | 1 | 2.5 | 0 | 0 |

According to the research the internal rate of return method and the payback method were the most commonly in use. As noted before, the former emphasises the profitability effect of an investment and the latter emphasises funding effect. The internal rate of return method was the most common principal method. In addition, all the corporations used non-financial methods for the analysis as well. (Neilimo & Uusi-Rauva, 2001)

## 4.3. Other affecting factors and people

One notable fact of the B2B markets is the large amount of people to participate the buying decision. Obviously, neither a production engineer nor a financial controller can decide by themselves that certain production equipment is to be bought. Webster and Wind introduced for the first time the different roles of company's buying centre in 1972 (Webster & Wind, 1972).

According to Webster and Wind (1972), there are six different roles in the buying centre: users, influencers, deciders, approvers, buyers and gatekeepers (see Figure 4.4). Users are the ones to use the product. They usually make a buying proposal and define roughly product specifications. In addition, they will be affected mostly on the quality of the product or service. Influencers are other persons that might influence to the buying decision. They are usually technical personnel who provide alternatives and help with the product specifications. Deciders decide finally on the product specifications and suppliers. Approvers are above the deciders and buyers. They authorize them to make the decisions. Buyers might influence a bit to the product specifications, but they are mostly responsible for supplier selection and negotiating. Gatekeepers are additional personnel who might prevent the information to reach the buying centre, e.g. buying agents, receptionists and telephone operators. Engineering personnel has usually the greatest influence to select a certain product. (Webster & Wind, 1972)

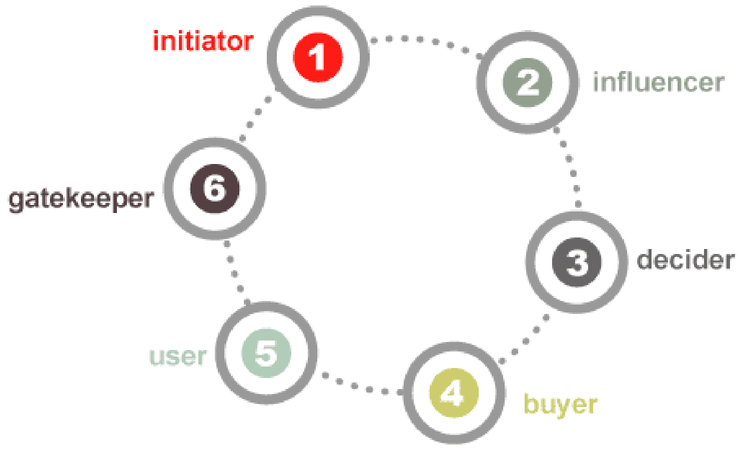


***Figure 4.4.*** *Roles in the buying centre*

When buying production machines, equipment or systems, the roles could be for example: User is a process owner or a production engineer who ramps up production of a new product. A certain process requires upgrade or totally new production equipment, and he or she makes a buying proposal. Influencers are other production engineers and financial controllers supporting the selection. Engineer of e.g. technology and development or R&D department provide alternatives and analyse their strengths and weaknesses. Controllers, on the other hand, can analyse financial impact and profitability of the alternatives, q.v. sections 4.1 and 4.2. Decider is the production manager, authorized by the CEO or the manager of the business unit. Buyers are the personnel of the purchase department. They negotiate the deal, or deals if there are more than one suitable option. Finally, there might be additional personnel preventing an equipment supplier from connecting the people mentioned above.

## 4.4. An example of an investment

For example, the marketing department of a company has exposed a new customer need. The R&D department has managed to develop a suitable product for the need. The product has an estimated life cycle of five years. According to a market survey, the product will profit the company 140,000€ each year in average. According to the production engineers, new automation equipment is needed in order to produce the precise features of the product. The engineers of technology department have investigated the options and there seems to be two suitable two options for the system.

The option A utilizes traditional technology and it costs 500,000€ (figure 4.1). However, the option B utilizes new kind of technology. It has slightly smaller modules and, supposedly, it is more flexible and modular. Therefore, the price is 600,000€. According to previous experience of technology A, the annual costs of usage are 45,000€ and the equipment could be sold with 250,000€ after five years of usage. Instead, there is not much experience with the technology B. Because of decreased energy consumption and floor space usage, it is estimated that the annual costs of usage are only 20,000€. A rough estimation is that the equipment could be sold also with the same price, 250,000€. The company has a standard discounting rate of 10% for investments in machinery. To simplify, there is no inflation.

The financial controller has calculated the numbers. According to present value method, the option A has a *NPV* of 15,355€ and the option B has a *NPV* of 10,124€. According to equivalent annuity method, the option A has an equivalent annuity of 4,051€ and the option B has an equivalent annuity of 2,671€. According to internal rate of return method, the option A has an *IRR* of 11.0% and the option B has an *IRR* of 10.5%. According to payback method, the option A has a payback time of 5.3 years and the option B has a payback time of 5.0 years. According to the first three methods, the option A is better investment. However, according to the payback method, the option B is better. The calculations are attached in the appendix 3.

However, not only the controller has something to say. The production engineers favour the option B. Even though it is slightly more expensive, it is modular and thus it could be used to produce multiple products in the future. Smaller modules would be a benefit as well. The business has expanded during last years and the production is likely to run out of space in the future. The engineers of technology department agree on the benefits.

However, they are really concerned on the robustness. The technology of the option B is new, and the industry does not have much experience with it. According to specifications and tests, both options have relative similar precision, speed and other important factors. The production manager also finds the option B interesting. However, in the end, he inclines to the option A. After all, it is more profitable investment and the company has a lot of experience with the technology. The company behind the option B is quite young and technical support in the future is a small concern. Last year they made a bit incautious machine investment, and he does not want it to happen again. The CEO agrees on the production manager and the option A is bought.

## 4.5. Observations from the interviews

Four principal topics came up in the interviews when speaking about investments in production technology. First, companies have relative short payback times. Investment calculations usually favour cheaper product specific systems. Secondly, the investments are usually based on process requirements. Production engineer based process development is rarely the case. Third, non-financial arguments have large impact on the decisions. Fourth, savings on labour costs are rarely the principal argument for automation. Instead, automation is justified usually e.g. by quality and repeatability.

VTT had a two year *Desktop Assembly* project between 2007 and 2009. The goal was to develop a desktop assembly concept for light and small sized products. As a result, a modular and small-size floor-standing system was developed. However, Timo Salmi (2011) argues that, according to his observations, the current cost accounting methods do not support modularity. Companies have payback times between one and four years. In some cases the payback times can be as short as months. As a result, product specific equipment overcomes modular platforms (Salmi, 2011). In other words, cost accounting does not usually support more expensive and versatile production technology.

Biohit is a Finnish company in the bio industry specialized in liquid handling products. The operations manager, Kalle Härkönen (2011) argued that companies have too narrow point of view with investments. Many companies tend to favour smaller investments as smaller risks are included. Therefore, only small improvements are usually achieved. Instead, Biohit analyses and develops whole value stream at a time. As a result, major value for the customer or for Biohit should be achieved. However, the payback times vary between couple months and couple years. The money has to circulate after all. (Härkönen, 2011)

Verkkokauppa.com is a Finnish home electronic retailer. In addition they offer product customization services. According to the production manager Pekka Tirkkoneen (2011), the payback time is about two years and one of the primary concerns are quality, reliability and technical services. (Tirkkonen, 2011)

Jari Luotonen (2011) summarizes that Nokia's investments in production equipment are always based on a business case. Payback times for standard hardware vary between three and five years. Occasionally, the payback times are notably shorter, depending on how many products the production equipment is to be applied for. If the equipment is only for one product, the payback time has to be shorter than the product's life cycle. If the equipment is bought for many products, payback time can be years. However, the latter case includes a risk that the product technology changes within the payback time. In addition to financial meters, ISO quality standards and twenty-four-seven technical support is required for the suppliers. Automation is compared to human recourse costs case by case. However, only the machine operator can be usually replaced. Requirement for maintenance personnel remains the same or increase instead. In the mobile device industry, manual production in Asia still outplays automation. However in Asia, the problem is availability and a high turnover of suitable labor. (Luotonen, 2011) Andy Zott states that a one year is quite standard payback time at Nokia (Zott, 2011).

Tomi Pietari (2011) estimates that savings on labor costs are an argument for automation at Vaisala. However, the quality of products is the primary concern in the production. Manual production is justified in many cases by the quality. An investment is always based on a risk analysis. Process has to provide stable quality now and in the future. Product's components and suppliers' technical support on maintenance and ramp-up are analyzed. The layout of new machinery has to fit into the current production. However, small size is not a principal argument. (Pietari, 2011)

Harri Heino (2011) stated that Bioretec concentrates on the technical specifications. Old machinery is used whenever it is possible. However, once in a while new machinery is needed for new processes. The specifications as well as strict standardization of bio industry are principal concerns. Product's sales potential and profits are estimated, and cost analysis is based on payback method according to his knowledge. (Heino, 2011)

Asyril is a Swiss company focused to miniature delta robots, feeding systems and miniaturized production cells. The CEO Alain Codourey (2011) emphasizes that a company buys a certain process. Equipment or machines are evaluated based on whether or not it does what it is supposed to do. If there are many options, other factors, e.g. price, quality and size of the equipment, will be evaluated. (Codourey, 2011)

Mika Laitinen (2011) states that in the mechanical engineering industry, the investment evaluations vary considerably between low and high value added businesses. In the low value added businesses, e.g. in car industry, main concern is the price per kilogram of finished product. According to his observation, in 90% of the cases in Finland, cost of automation is evaluated against costs of labor. In the high value added businesses, e.g. in the aviation industry, the automation is justified e.g. by work safety and quality. Supporting to micro and desktop production system, one argument is automation capacity per square meter. (Laitinen, 2011)

# 5. DEVELOPMENT OF MICRO AND DESKTOP PRODUCTION SYSTEMS

According to Okazaki et al. (2004), the idea of a microfactory originates from the research conducted in Japan in the 1990's. The Micromachine Center (MMC) was established in 1988. Between 1991 and 2000, national universities, research centres and corporations worked on the project Micromachine Technology. The research was based on an idea that smaller machines might be needed to produce micro parts and machines. Energy saving and economizing were primary goals. Within the project, smaller machines and equipment were developed. Ideas of "desk-top", "palm-top" and "mobile" factories were awoken. (Okazaki et al., 2004) Subsequently, the research spread around the world, and multiple concepts, of miniaturized production systems and machining units, have been introduced. Afterwards, topics such as modularity, virtual models, cleanrooms and high-precision manufacturing have been included into the research.

Microfactory and desktop factory are the terms normally used to describe highly miniaturized manufacturing systems and equipment. The terms "mini factory" and "factory-in-a-suitcase" are mostly historical. In other occasions, the same terms might refer to e.g. 3D-printing (Desktop Factory, 2011) and infrastructure software (Rosenthal & Schmitz-Homberg, 2010). Within the manufacturing research, the prefix micro might refer to micro-size manufacturing, small manufacturing equipment or both. Desktop Factory® (or DTF®) is an officially registered trademark by NIDEK Sankyo Corporation, which is a key member of the Japanese DTF Research Consortium.

Within the academics, at least four types of concepts have been developed under the terms "micro factory" and "desktop factory" (q.v. 5.1.1 – 5.1.4). In the industry, the breakthrough remains still unseen. There are some commercial microfactory platforms on the market. In addition, commercial miniaturized robotic stand-alone cells, as well as machining units and 3D printers have been developed.

Both academic research and commercial equipment development are discussed in this chapter. The section 5.1 discusses the academic research and concept development. The section 5.2 summarizes the microfactory research at TUT. The section 5.3 introduces examples of small-size production equipment. Finally, the section 5.4 points out some of the observations from the interviews. For more detailed description about the academic concepts and commercialized units, please refer to the appendix 6. The years in Tables 5.1 – 5.12 refer to the year a given concept or product is first published or launched, according to the author's knowledge and available information.

## 5.1. Academic microfactory concepts

The academic microfactory concept building is nothing but homogenous. Under terms "microfactory" and "desktop factory", at least four types of concepts have been developed: sets of small-size production equipment, modular microfactory platforms, miniaturized machining units and miniaturized robotic cells. The different concepts of the four categories are discussed in this section. For more detailed description about the academic concepts, please refer to the appendix 6.

### 5.1.1. Microfactory as a set of small-size production equipment

The original Japanese approach to microfactory is to develop a fixed set of integrated small-size production machines. The systems are mostly tele-operated, i.e. the operator uses the machines via joystick or other devices (see Table 5.1 and Figure 5.1).

***Table 5.1.*** *Traditional academic microfactory concepts*

| Year | CC | Concept | Institute | Source |
|---|---|---|---|---|
| 1994 | JP | **Microfactory by MMC** or Experimental Microfactory System | MMC (& companies) | Ataka, 1999<br>Ogawa, 2000 |
| 1998 | JP | **Portable Microfactory** or Desktop Machining Microfactory | AIST (MEL) | Kitahara et al., 1998<br>Tanaka, 2001 |
| 2000 | FIN | **TOMI Microfactory** | TUT | Tuokko et al., 2000<br>Tuokko, 2002 |
| 2006 | USA | **Automated Illinois Microfactory** | UIUC | Honegger et al., 2006a<br>Honegger et al., 2006b |
| 2006 | KR | **Mosaic** | KIMM | Park et al., 2007 |

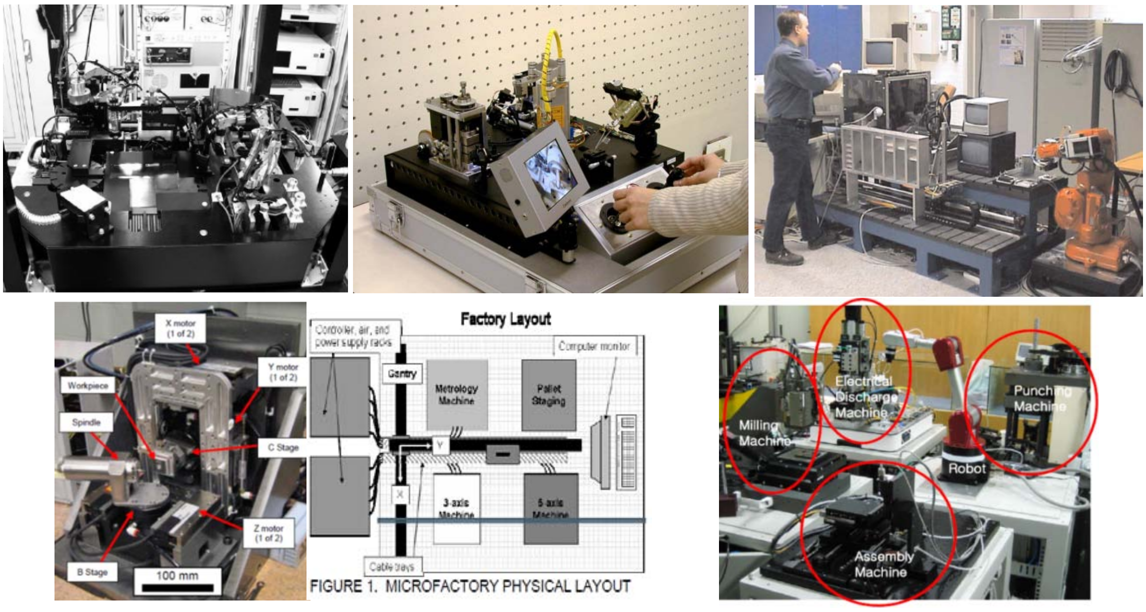


***Figure 5.1.*** *Microfactory by MMC (Ataka, 1999), Portable Microfactory (Tanaka, 2001), TOMI Microfactory (Tuokko, 2000), Automated Illinois Microfactory (Honegger et al., 2006a, 2006b) and Mosaic (Park et al., 2007)*

The microfactory systems include ordinarily miniaturized machining units and/or micro-press to produce the components, a small-size manipulator, a transfer arm or a conveyor system to transport the components, and a small-size assembly unit or a micro-manipulator to assemble the components. In author’s point of view, the primary goal of the research has been miniaturization of the machines. As a result, versatile microfactory architectures and systems were developed. Terms such as “factory-in-a-suitcase” and “portable microfactory” arose with the research.

One of the first microfactory concepts, Experimental Micofactory System, was developed in Japan in the 1990’s. Dimensions of the system are 600x650x750mm. It was developed e.g. for production of micro-mechanics. The system consists of a conveyance unit, a processing unit and an assembling unit. The assembling unit includes two micro-arms, a precise stage and several working tools. The processing unit includes electrochemical machining device, micro-pumps and recognition device. (Ataka, 1999)

Another famous Japanese microfactory concept is the Portable Microfactory developed by MEL in 1998. Dimension of the system are 625x490x380mm, and it is tele-operated. The user interface consists of two joysticks and a 5.8-inch LCD monitor, showing video of three miniature CCD cameras. The system has a micro lathe, a micro-milling machine, a micro-press machine, a transfer arm and a two-fingered micro manipulator. Miniature ball bearing was used as the first trial product. (Tanaka, 2001)

One of the first international microfactory concepts was the TOMI Microfactory developed by TUT in Finland in 2000. TOMI (Towards Mini and Micro Assembly Factories) was a pilot project for TUT microfactory research. The goal was to develop an integrated high performance assembly system for a miniature product. The case product was a planetary gearhead with a diameter of 8 mm and variable gear ratios. As a result, a small-size floor standing system was developed. Dimensions of the production system are 1800x500mm. In addition, the system consists of modules of 500x500mm. All the assembly phases were packed into one cell. (Tuokko, 2002)

A concept of automated microfactory was developed at University of Illinois at Urbana-Champaign (UIUC) in USA in 2006. The system is based on a 900x900mm pneumatic vibration isolation table. Individual machines locate horizontally on the table and they are operated by a computer. Machine development included a three-axis and a five-axis milling/drilling machines as well as a metrology station. Specific pallets were developed to transfer the parts. (Honegger et al., 2006a, 2006b)

Korea Institute of Machinery & Materials (KIMM) developed their first microfactory in 2006. The system consists of a micro milling machine, an electrical discharge machine, a manipulator, an assembly machine and a punching robot. The machines have floor standing bases. The system was used to manufacture a micro pump. (Park et al., 2007)

### 5.1.2. Miniaturized machining units

Parallel to the microfactory research described above, multiple highly miniaturized machining units have been developed since the mid 1990's. Some of them have been developed for the microfactory concepts described in the previous sub-section and some are developed for stand-alone use. They are usually high-speed and high-precision machines designed to produce metallic precision mechanics components. Terms such as "palm-top factory" and "mini factory" arose with the research. This section introduces six concepts (see Table 5.2 and Figure 5.2).

***Table 5.2.*** *Academic miniaturized machining units*

| Year | CC | Concept | Institute | Source |
|---|---|---|---|---|
| 1996 | JP | **Microlathe** | MEL | Kitahara et al., 1998 |
| 1999 | JP | **Multifunction desktop machine** | AIST | Kurita et al., 2001 |
| 2000 | JP | **NC Microlathe** | AIST (MEL) | Okazaki & Kitahara, 2000 |
| 2001 | JP | Desk-Top NC Milling Machine, 200krpm ("**El Chuchito**") | AIST | Okazaki et al., 2001 |
| 2004 | JP | **Desk-Top Milling Machine**, 300krpm | AIST | Okazaki, 2004 |
| 2004 | MX | **Mexican First Generation MMT** | UNAM | Ruiz-Huerta et al., 2004 |

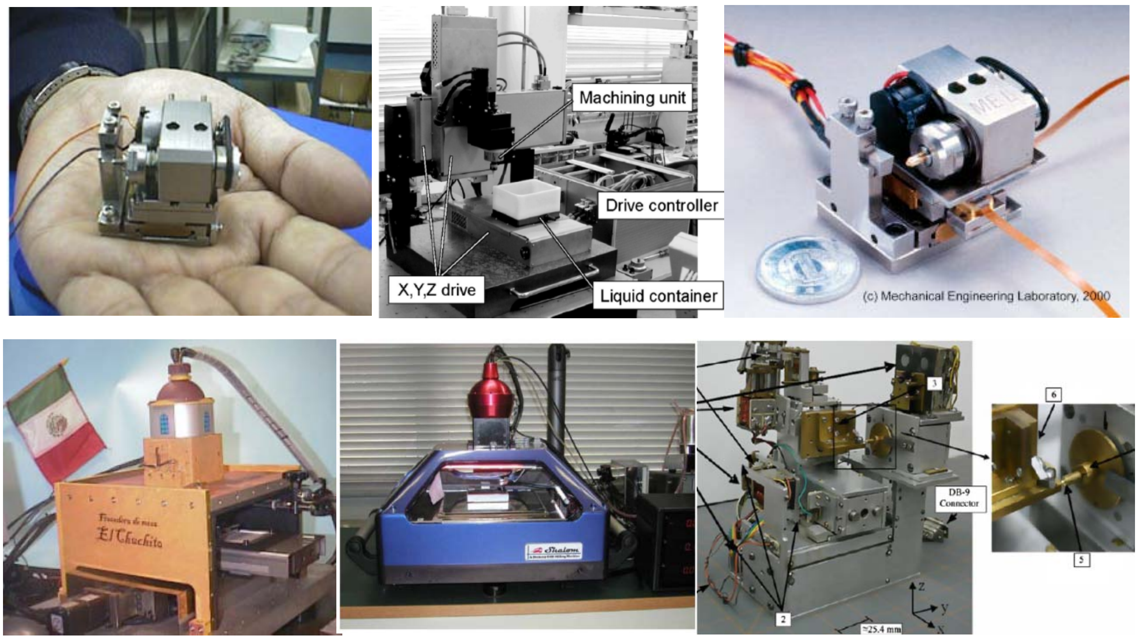


***Figure 5.2.*** *The original Microlathe (Kitahara et al., 1998), Multifunction desktop machine (Kurita et al., 2001), Microlathe with numerical control (Okazaki & Kitahara, 2000), "El Chuchito" (Okazaki et al., 2001), Desk-Top Milling Machine (Okazaki, 2004) and Mexican First Generation MMT (Ruiz-Huerta et al., 2004)*

The first and one of the most commonly cited machine is the microlathe developed in Japan in 1996. The lathe revealed the possibility to downsize machining units. The lathe has dimensions of 32.x25.0x30.5mm and it weights 100g. The main spindle motor uses only 1.5W, and it can turn up to 10,000rpm. It has an accuracy of 1.5µm in the feed direction and a roundness of 2.5µm. The minimum diameter of work is 60µm. (Kitahara et al., 1998, according to Okazaki et al., 2004) Four years later, in 2000, the microlathe was succeeded to equip with a precision digital control system. A desktop milling machining unit, with a footprint or 550x450mm, was build based on the NC (numerical controlled) microlathe. (Okazaki & Kitahara, 2000, according to Okazaki et al., 2004)

Downsizing also lead to development of high-speed spindles. “El Chuchito”, developed by AIST, was one of the first miniaturized high-speed milling machines. It has dimensions of 450x300x380mm and a maximum spindle speed of 200,000rpm. It includes a numerical control system with 0.1µm resolution. The total power consumption under high-speed machining is 120W. (Okazaki et al., 2001) In 2004, the system was revised. The new machine includes a 300,000 rpm spindle. It is slightly larger, having dimensions of 480x480x470mm and a weight of 42kg. The power consumption also rose up to 400W. However, it is more accurate because of the linear XY stage. (Okazaki, 2004)

Downsizing of machining tools also led to development of multifunction machining units. Just before millennium, a prototype of multifunctional machining unit was developed by AIST and new AIST. The machine has dimensions of 557x604x655mm and a weight of 80kg. There are five changeable machining units: high, middle and low speed spindles, laser irradiation unit and piezoelectric actuator unit. As a result, multiple machining methods are enabled: milling, drilling, cutting, grinding, polishing, EDM, ECM, laser machining and laser treatments. (Kurita et al., 2001)

Another example of micromachine development is the microequipment developed in Mexico in the early 2010 decade. The first generation had dimensions of 130x160x85mm and the second generation was slightly larger. They based on small-size stepping motors. In order to decrease the price of the equipment, a lot of low-cost materials and only few commercial components were used. (Ruiz-Huerta et al., 2004)

### 5.1.3. Modular micro and desktop factory concepts

In addition, a slightly different approach to microfactory exists. The concepts described in this sub-section are primarily modular microfactory platforms and/or architectures. In general, the main focus of the research is developing the platform. Consequently, manipulators, actuators and other process equipment have been developed for the platforms. Terms such as “modular microfactory” arose with the research. This section introduces seven concepts (see Table 5.3 and Figure 5.3). TUT Microfactory is described more extensively in the section 5.2.

***Table 5.3.*** *Academic modular microfactory concepts*

| Year | CC | Concept | Institute | Source |
|---|---|---|---|---|
| 2001 | USA | **Agile Assembly Architecture** | CMU | Rizzi et al., 2001 |
| 2001 | GER | **AMMS**, Advanced Modular Microassembly System | Frauenhofer IPA | Gaugel & Bengel, 2001; Gaugel et al., 2004 |
| 2004 | FIN | **ABAS Desktop Platform** | TUT | Lastra, 2004; Jokinen, 2006; Jokinen & Lastra, 2007 |
| 2005 | CH | **Microbox Pocket-Factory** | EPFL (LSRO) | Verettas et al., 2005 |
| 2005 | FIN | **TUT Microfactory** | TUT | Heikkilä et al., 2007; Heikkilä et al., 2010 |
| 2008 | JP | **Module-Based Microfactory** | AMRI & new AIST | Nakano et al., 2008; Ashida et al., 2010 |
| 2010 | CH | **Rotary Assembly Line** | EPFL (LSRO) | Kobel & Clavel, 2010 |
| 2011 | FIN | **Desktop Asesmbly** | VTT | see VTT, 2011 |

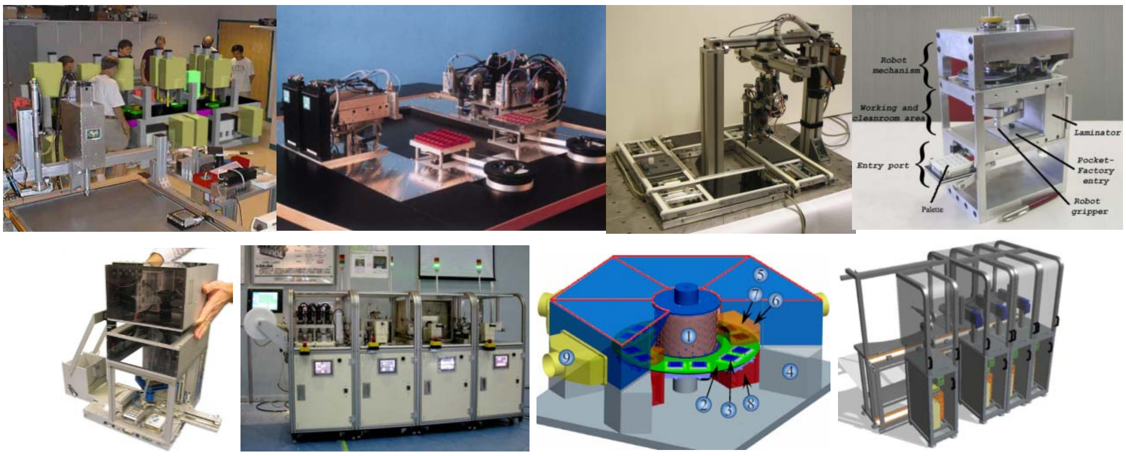


***Figure 5.3.*** *AAA (Rizzi et al., 2001), AMMS (Gaugel et al., 2001), ABAS (Lastra, 2004), Microbox (Verettas et al., 2005), TUT Microfactory, Module-Based Microfactory (Nakano et al., 2008), Rotary Assembly Line (Kobel & Clavel, 2010), Desktop Assembly*

One of the first modular microassembly concept was the Agile Assembly Architecture (AAA) developed by Carnegie Mellon University in Pittsburgh USA in 2001. It is a floor standing system and thus slightly larger than normal microfactory concepts. The system is divided into “minifactory” segments, each of which includes a modular base frame, a planar table, precision part feeders and an overhead 3DOF manipulator. The development started in the mid 1990’s. It was designed for e.g. assembly of magnetic storage devices, small computers and other high-density products. (Rizzi et al., 2001)

One of the first modular desktop-size microfactory concepts was the Advanced Modular Microassembly System (AMMS), developed by Frauenhofer IPA in Germany in 2001. The “plug-and-produce” system is based on a 600x400mm planar motor table manufactured by L-A-T Suhl AG. Products and/or components are placed on moving couriers, which move with a friction-free air bearing on the planar table. The fixed process modules have dimensions of 100x200mm, and they are placed next to the planar table having standardized interfaces. The complete system has dimensions of 800x800mm. The XY planar stage has a positioning accuracy of 20μm. The accuracy of other axis depend the process modules. A miniaturized laser diode was used as a case product. It is argued that a wide range of micro products, e.g. mini-encoders, micro-valves or fiber-optics, could be assembled with a similar system. (Gaugel et al., 2004)

An example of Rapidly Reconfigurable Manufacturing Systems (RRMS) is the Actor-Based Assembly Systems (ABAS) developed by Tampere University of Technology (TUT) in Finland in 2004. ABAS is general agent based architecture to link the available assembly actors to needed assembly operations in a complex manufacturing system. As a pilot, a desktop size intelligent material handling system was constructed. It identifies the optimal route for the pallet, based on the process requirements and the available processes. Interfaces of the conveyor modules include power, pneumatics and communication. In addition, it identifies of the location on the base plate on the courier system. Such systems are developed for short product life cycles and mass customization. (see Lastra, 2004; Jokinen, 2006; Jokinen & Lastra, 2007)

The first microfactory concept with an integrated cleanroom was the Microbox Pocket-Factory developed by LSRO (a laboratory of EPFL) in Switzerland in 2005. Microboxes have cleanrooms capable of clean class 100 or ISO 5 (i.e. max. hundred thousand articles of size ≥0.1μm in a cubic meter). In addition, the units include an entry port enabling clean transfer into unit, a 4DOF scara robot for easy assembly tasks, sensors for process control, a laminar airflow generator and a filtration system. The units have about 1$dm^3$ clean working area. Although some prototypes were built, the optimal size of the units was one topic of the research. A “Pocket-Factory” can be constructed out of multiple Microbox units and different feeders. Each unit can conduct one or multiple assembly operations (e.g. gluing and insertion). (Verettas et al., 2005)

The microfactory research at EPFL has continued with another concept, Rotary Assembly Line. It is developed to achieve higher clean classes than with linear concepts. The circular concept has a central unit including clean air inlet, rotary table for transportation of standard 2” trays and interfaces (mechanic, data and power) for the production modules. The production modules around include working area with laminar and horizontal air flow, space for a manipulator, air outlet, as well as inlets and outlets for the components. The modules have dimensions of about 250x250mm and height of 75mm. The overall system has a footprint smaller than a square metre. One prototype with two modules is already built. (Kobel & Clavel, 2010; Kobel, 2011)

One often used term within microfactory research is micro-electro-mechanical systems (MEMS). MEMS products are for example digital micro mirrors and sensors. It is expected that microfactories could be used to produce effectively MEMS products. In Japan, AMRI and new AIST developed an on-demand production system for MEMS devices in 2008. The system is based on modular microfactories. Dimensions of the floor standing modules are 500x800x1200mm. The worktable is 750mm high. The modules include a PLC, a transfer unit, a process unit and connections (power, compressed air and communication) to other modules. The concept was demonstrated by production of a metal-based micromirror scanner. (Ashida et al., 2010)

One of latest microfactory-related projects in Finland is the DesktopAssembly managed by The Research Centre of Finland (VTT). Objective of the project was to develop desktop assembly concept for light and small-sized products. As a result, a concept of modular floor standing system was developed. The system includes a smart conveyor system, standardized base modules and specific process modules. The control system is designed to work as a "plug and produce". (see VTT, 2011; Marstio, 2011; Salmi, 2011)

### 5.1.4. Miniaturized robotic and assembly cells

This sub-section describes the fourth category of academic microfactory concepts. The concepts are miniaturized stand-alone assembly systems, having usually one or few manipulators and one or few cameras for tele-operation. They are mostly semi-automatic. Four systems are introduced (see Table 5.4 and Figure 5.4).

***Table 5.4.*** *Academic miniaturized robotic cells and assembly units*

| Year | CC | Concept | Institute | Source |
|---|---|---|---|---|
| 2002 | CH | **Flexible Microassembly Cell** | EPFL (LPM) | Koelemeijer Chollet et al., 2002 |
| 2003 | GER | **µFemos** | KIT | Bär, 2006 |
| 2004 | FIN | **Mini assembly cell** | TUT | Uusitalo et al., 2004 |
| 2008 | TR | **Versatile and Reconfigurable Microassembly Workstation** | Sabanchi University | Kunt et al., 2008 |
| 2008 | FR | **Flexible Micro-Assembly System with Automated Tool Changer** | FEMTO-ST | Clévy et al., 2008 |
| 2011 | GER | **Robotic Systems for High Throughput Bio Analytics** | KIT (AIA) | Pfriem et al., 2011 |

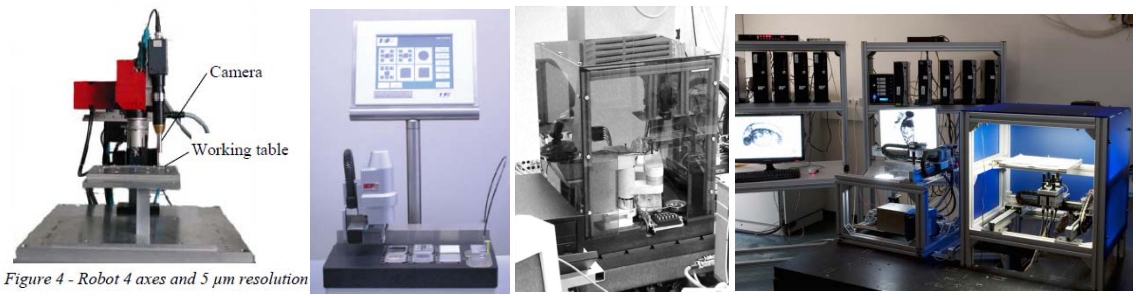


***Figure 5.4.*** *Flexible Microassembly Cell (Koelemeijer Chollet et al., 2002), µFemos (Bär, 2006), Mini assembly cell (Uusitalo et al., 2004), Robotic Systems for High Throughput Bio Analytics (Pfriem et al., 2011)*

Some of the first microassembly systems were the Flexible Microassembly Cells developed by EPFL in 2002. At the time, two cells were developed. Both of them have a working space of approximately 150x150x150mm and one camera for vision system. They are designed for small and medium sized batches. The low-resolution cell has a 4DOF robot with a resolution of 5µm. The camera is integrated to the robot. The high-resolution cell includes a 6DOF robot with a resolution of 0.5µm and a 3DOF robot for clue dispensing. The vision system is integrated into the Z-axis of the 6DOF robot, keeping the gripper within the field of view all the time. The system was demonstrated by semi-automatic assembly of a watch plate. (Koelemeijer Chollet et al., 2002)

Some of the concepts include more automation and multiple processes in one cell. The µFemos was developed by KIT in Germany in 2003. The system includes a 4DOF cartesian axis system (XYZ and rotation). The dimensions are 600x600x500mm (an A3 paper size.). It was developed for assembly of an optical distant sensor with height precision. Multiple cells were sketched in line but it was not demonstrated. (Bär, 2006)

The mini assembly cell was designed for assembly of mini-sized planetary gearheads in 2004. The system has a footprint of 500x500mm. It was designed for the TOMI Microfactory. (Uusitalo et al., 2004) A Versatile and Reconfigurable Microassembly Workstation was developed by Sabanci University and Gebze Institute of Technology in Turkey in 2008. The desktop-size system includes two 3DOF micromanipulator stages and a 3DOF sample precision positioning system, as well as a vision systems with 3DOF, two CCD cameras with magnification of 4x-800x. (Kunt et al., 2008)

Two main concerns of micromanipulation are the fragile components and the sticky effect. As components get smaller gravity becomes insignificant. Adhesion and other surface forces become dominant instead. In addition, small parts tend to be fragile. As a result, vacuum grippers might destroy the small parts and releasing becomes difficult. Therefore, more sophisticated grippers need to be developed. One example is the Flexible Micro-Assembly System developed by FEMTO-ST in France in the end of the 2010 decade. The desktop-size system includes a XYZ positioning table, a camera and specially designed piezoelectric gripper with an automated tool changer. The gripper includes two piezoelectric beams. The positioning accuracy is about 3µm. The system is tele-operated with a joystick and a screen. (Clévy et al., 2008)

At the moment, the Robotic Systems for High Throughput Bio Analytics is under development at KIT. According to Pfriem et al. (2011), the system is developed for sorting and recognition of zebrafishes. Currently the process, of breeding, pipetting, microscoping and analysing, is mainly manual. It takes approximately 14 minutes for a researcher to sort manually 384 chambers. In addition to saving in time, the system can maintain a constant temperature of 28°C. (Pfriem et al., 2011) The system reveals interesting potential in laboratory automation. Laboratory processes and bio analytics have a lot of repetitive tasks (e.g. pipeting), which are conducted fully manually.

## 5.2. Research at TUT

The research of miniature production systems has been one of the key topics at Department of Production Engineering at Tampere University of Technology since 1999 (Tuokko, 2006). The latest concept, TUT Microfactory, has been developed since 2005. The research is typical modular microfactory research, q.v. 5.1.3. In other words, the main focus of the research is to develop the microfactory platform, e.g. designing interphases, control system and modular structure. Development of e.g. robots, process modules and end-effectors are designed for the platform.

This section gives a short introduction to the microfactory research at TUT. For more detailed description about the microfactory research at TUT, please refer to (Tuokko, 2006) and (Tuokko & Nurmi, 2011). For more detailed description about the TUT Microfactory concept, please refer to (Heikkilä et al., 2007), (Siltala et al., 2010a) and (Heikkilä et al., 2010). The sub-section 5.2.1 introduces the TUT Microfactory concept, the projects are discussed in the sub-section 5.2.2. The sub-section 5.2.3 summarizes different demonstrations realized with the TUT Microfactory.

### 5.2.1. TUT Microfactory concept

The TUT Microfactory concept is based on small independent microfactory cells (see Figure 5.5). A TUT Microfactory module has dimensions of 300x200x220mm and a working space of 180x180x180mm. All the needed auxiliary systems are included. The modules are designed to work as a stand-alone unit or as a part of “plug-and-produce” production line. Each module has an individual control unit and standardized interphases. They can communicate with each other through the physical connections or through WLAN. User interface for a tablet PC has been developed. One or multiple cells can be controlled with a single device. (Heikkilä et al., 2007)

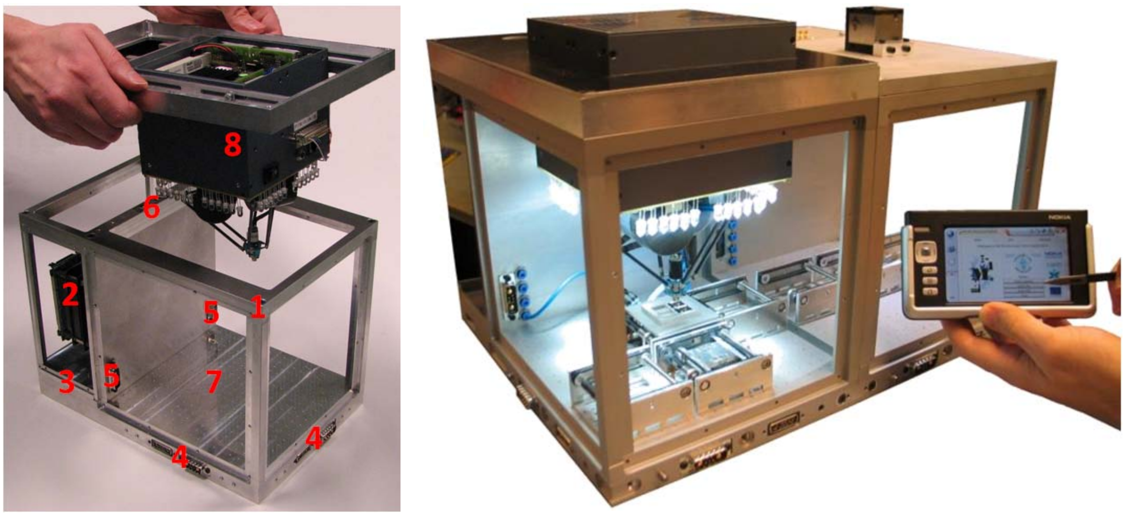


***Figure 5.5.*** *On the left: The structure of TUT Microfactory (Tuokko & Nurmi, 2011) On the right: TUT Microfactory (Heikkilä et al., 2007)*

The TUT Microfactory module includes (1) an aluminium body including the air inlets, (2) a PC104-size control cabinet (including a control PC, a low-level housekeeping electronics board and extra space for components of the process devices), (3) the cleanroom system, (4) hybrid cell-to-cell interphases (with an interlocking system, 24 VDC power lines, 100 Mbit Ethernet and tubes for pressurized air), (5) interphases for process equipment inside the cell, (6) an interphase for the process module (slightly different than the cell-to-cell interphase), (7) air outlet holes (HEPA filters, cleanroom electronics and fans are to placed under the floor) and (8) a process module (including here an Asyril PocketDelta robot) (see Figure 4.5, on the left). (Heikkilä et al., 2007)

As stated above, the modules work as an independent unit or as a part of a production line. The production line can be constructed relative freely out of the modules. Because of the current mechanical connections, three possible connections are restricted, i.e. front-by-front, front to the right side and side by side against each other (at the control cabinet side of the cell). Apart from these three cases, multiple different kinds of lines, cells and loops are possible. Also a fish bone structure is possible. (Siltala et al., 2010)

Also different robots and subsystems have been developed for the concept as well. The robots include e.g. the 3DOF TUT H-Belt Robot (Vuola et al., 2010a), the 4DOF TUT H-Scara Robot (Vuola et al., 2010b) and the inexpensive 3DOF TUT LM Robot (see Tuokko & Nurmi, 2011, p.5). The subsystems include, for example, a modular conveyor system (Heikkilä et al., 2010) and an adaptive gripper system, developed in co-operation with Korea Institute of Machinery and Materials (KIMM) (Prusi et al., 2012). Moreover, a spin-off Wisematic has commercialized the machine vision based flexible feeding system, Minifeeder ™, developed a TUT (Wisematic Oy, 2010).

### 5.2.2. Projects

Until now, there have been seven microfactory-related research projects at TUT (see appendix 4). TOMI (Towards Mini and Micro Assembly Factories) was the pilot project between 2000 and 2002 (Tuokko, 2006). During the project, a real-scale pilot system was developed, q.v. 5.1.1. The overall target of the project was to gain experience in precision assembly of miniature, micromechanical, and microelectromechanical products (Tuokko, 2003). The second project, Beyond Mini Technologies, focused on e.g. handling and assembly of small parts, micro grippers and end effectors, machine vision systems and micropart joining.

Five ultimate projects relates to the TUT Microfactory concept described above. During the first project, M4, the concept was developed and the first prototypes were built (e.g. Heikkilä et al., 2007). During the NEXT project, different alternatives and interphases were evaluated and the first actual modules were built. During the DESK project, desktop factory system and processes were further developed. For example, logistics systems were evaluated (Järvenpää et al., 2009) the flexible screwing cell was developed (Vuola et al., 2010a) and multiple demonstrations were conducted (e.g. Heikkilä et al., 2008; Siltala et al., 2011). The Mz-DTF project focused on factory level integration and multi-vendor systems. For example, different architectures and interphases were evaluated (Siltala et al., 2010a), the TUT Microfactory standards were created (Siltala et al., 2010b, 2010c), different robots were evaluated (Prusi et al., 2010) and a multi-vendor demonstration for mobile phone assembly was conducted (Tuokko & Nurmi, 2011, p. 7). During the latest project, DeskConcept, the ecologic and economic advantages of microfactories have been evaluated.

### 5.2.3. Demonstrations

During the microfactory projects at TUT, multiple demonstrations have been conducted. Six of them are introduced in this sub-section (see Figure 5.6). The first demonstration was an assembly of a mobile phone loudspeaker in 2005. The assembly was a pick and place operation from jig to the cell phone cover. In the demonstration, one TUT Microfactory with Asyril PocketDelta robot was used. A visual inspection system was used to place the speaker. (Heikkilä et al., 2007) In 2007, a laser marking microfactory was demonstrated at the Laser mess in Germany. The systems included two base modules, a 10W fiber laser and an optical scanner. The demonstration was an introduction to point-of-need manufacturing. (Heikkilä et al., 2010) In 2008, a spring assembly was conducted as the first industrial demonstration. The case was to assemble a miniaturized spring into component hole. One base module was used in the demonstration. (Heikkilä et al., 2010)

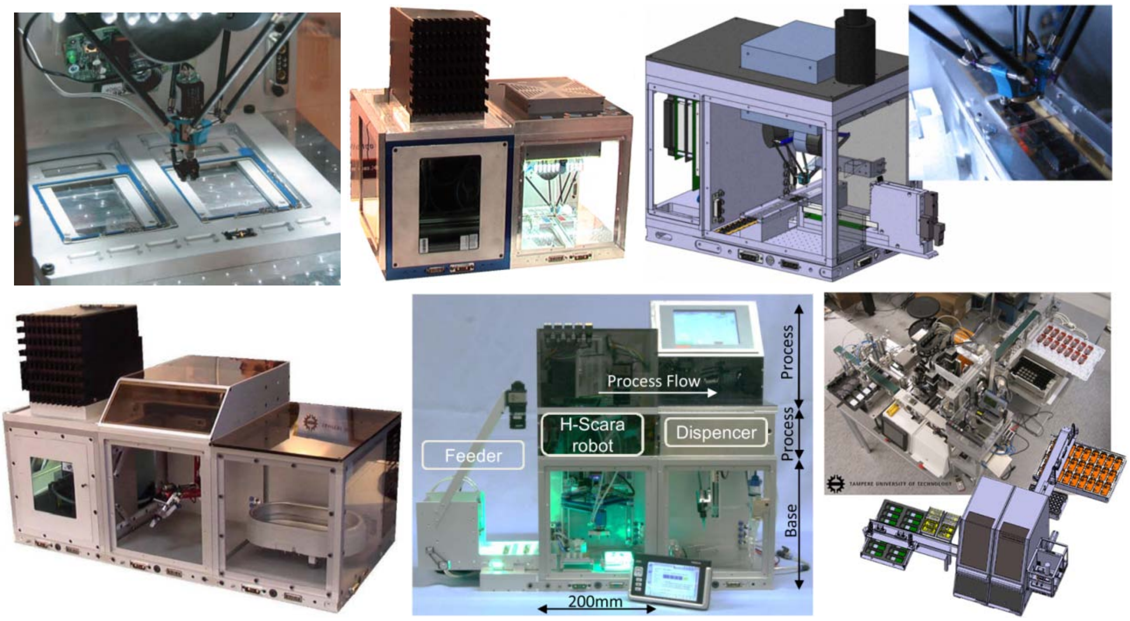


***Figure 5.6.*** *Mobile phone loudspeaker assembly (Heikkilä et al., 2007, p.170), Laser marking microfactory (Heikkilä et al., 2010, p. 121), Spring assembly (ibid., p. 123), Medical implant factory (Heikkilä et al., 2008), Gas sensor assembly system (Siltala et al., 2011), Integrated mobile phone assembly (Tuokko & Nurmi, 2011, p. 7)*

In 2008, the first medical demonstration was conducted. The case product was a small silicon rubber ear tube. A tree-module desktop factory line was set up for the demonstration. The first module included a laser lathe, the second module included a 5DOF articulated joint robot and the third factory was equipped with a small ultrasonic washing system. (Heikkilä et al., 2008) The gas sensor assembly was a good introduction to e.g. different joining methods. The assembly included four steps and the system was built up with two basic modules. (Siltala et al., 2011) Finally the mobile phone assembly system demonstrated the multi-vendor desktop factory (Tuokko & Nurmi, 2011, p. 7). TUT Microfactory module was used as a screwing cell.

## 5.3. Commercial small-size production equipment and machinery

This section presents some commercial micro and desktop production systems, as well as desktop-size rapid prototyping units. In addition, small-size hobby and educational machining units as well as 3D printers are presented. In conclusion, only few modular desktop factories have been developed. However, multiple commercial small stand-alone production units exist. So far, it appears that the miniaturized machining units have the largest coverage. Furthermore, desktop-size stand-alone automation units have been developed for multiple purposes. Desktop-size 3D printers and rapid prototyping units are appearing on the market as well.

### 5.3.1. Commercial micro and desktop factory cells

One of the first commercial microfactory units was the Desktop Factory® developed by NIKED Sankyo (former Sankyo Seiki) (see Table 5.5 and Figure 5.7). The modules are 170mm wide and they are designed for multiple purposes, e.g. cleaning, coating, screwing measuring and assembly. (Tuneda, 2005) Another famous Japanese microfactory unit is the Multi-Pro developed by Takashima Sangyo. Multi-Pro is a versatile 3-axis desktop machine platform. The dimensions of the system are 476x477x625mm. Besides designing and manufacturing of the machinery and equipment, Takashima Sangyo is manufacturing precision machined parts. Multiple processes, e.g. laser machining, precision processing and jig grinding, have been miniaturized. (see Endo, 2010; Takashima Sangyo, 2011)

In Europe, one of the first “Desktop Factories” was developed by German Bosch Rexroth AG. Despite the name, it is a modular floor standing system. However, the width of the modules is only 220mm. As a result, a 30m long automated assembly line can be squeezed up to 4.5m (Klemd, 2007). In 2010, a Finnish automation provider, Master Automation Group, introduced MAG Lean cells. In contrary to Bosch modules, MAG Lean is truly a desktop-size system. The dimensions of the 3-4 axis cells are 250x500x500mm and they weight only between 25kg and 40kg depending on the configuration. Applications include e.g. pick and place, screw inserting, testing and laser marking of aluminium, steel and plastic components. (MAG, 2010) In 2011, Master Automation Group merged together with another Finnish automation provider, JOT Automation. The recently published JOT Lean cell includes two sizes, 533x600x710mm and 333x600x710mm. Besides the applications above, plasma treatment has been states as a potential application as well. (JOT Automation, 2011)

***Table 5.5.*** *Examples of commercial multifunction micro and desktop factories*

| Year | CC | Product | Company | Source |
|---|---|---|---|---|
| 2003 | JP | **Desktop Factory DTF®** | NIDEK Sankyo Co. | see Tuneda, 2005 |
| 2003 | JP | **Multi-Pro** | Takashima Sangyo Co. | see Endo, 2010; Takashima Sangyo, 2011 |
| 2007 | GER | **Lean Desktop Factory** | Bosch Rexroth AG | Klemd, 2007 |
| 2010 | FIN | **MAG Lean** | MAG Oy | MAG, 2010 |
| 2011 | GER | **microFLEX** | IEF Werner GmbH | Hofmann et al., 2011; IEF Werner GmBH, 2011 |
| 2011 | FIN | **JOT Lean** | JOT Automation | JOT Automation, 2011 |
| 2012 | USA | **Nexar®** | Douglas Scientific | Douglas Scientific, 2012 |

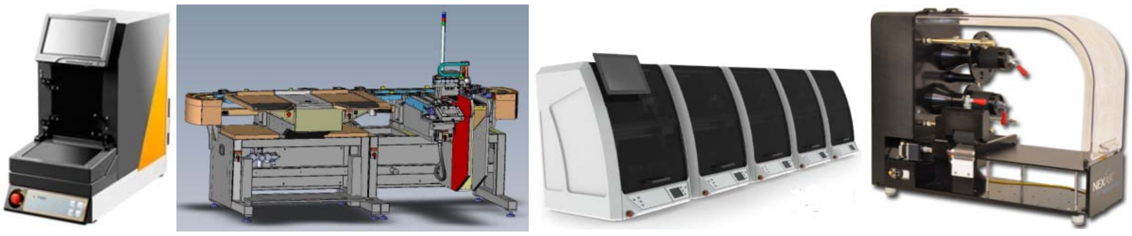

***Figure 5.7.*** *MAG Lean (MAG, 2001), microFLEX (Hofmann et al., 2011), JOT Lean (JOT Automation, 2011), Nexar (Douglas Scientific, 2012)*

In Germany, another floor standing system, microFLEX was developed by IEF Werner GmBH in cooperation with KIT. The system is based on 1200x800x800mm modules, including 800x1000mm space for processes and in/out buffers. The logistics system is based on 80mm standard trays and RFID tags. It is designed for different levels of automation (from manual to semi-automatic and full automation). The modules correspond to manual assembly tables in the industry the system was designed for. (Hofmann et al., 2011; Hofmann, 2011)

Furthermore, modular desktop-size systems have been developed for laboratory use. Nexar® is a modular liquid handling system for processing of sub-microliter volumes, developed by Douglas Scientific. The system is built for the Array Tape™ which enables high throughput processing. Instead of test tubes or a microtiter plate, the samples are sealed inside of tape rolls. Nexar® dispenses the samples, seals the tape and winds it onto the reel. Machine vision and a 3DOF linear manipulator are used to feed the wells. The modules have dimensions of 640x813x287mm and a standard configuration is 3211mm long. In addition, the system includes a floor standing PCR thermal cycler and a desktop-size fluorescence scanner. (Douglas Scientific, 2012)

### 5.3.2. Small-size stand-alone robotic, assembly and process cells

Some commercial small-size and stand-alone production cells have been developed as well. Here the machines are divided here into process (see Table 5.6 and Figure 5.8) and robotic cells (see Table 5.7 and Figure 5.9). In 2005, the Japanese Desktop Factory Consortium developed the Ultra Compact Hot Embossing Machine and the Desktop Nickel Plating Machine. The former is a floor standing machine and the latter is a desktop-size unit with dimension of 812×303×300mm. (see DTF, 2011)

***Table 5.6.*** *Examples of commercialized small-size stand-alone process cells*

| Year | CC | Product | Company | Source |
|---|---|---|---|---|
| 2005 | JP | **Ultra Compact Hot Embossing Machine** | DTF | see DTF, 2011 |
| 2005 | JP | **Desktop Nickel Plating Machine** | DTF | see DTF, 2011 |
| 2007 | UK | **DS2™** and **DSX™** | DYNEX Technologies | DYNEX Technologies, 2007a<br>DYNEX Technologies, 2007b |
| 2009 | IT | **Global240** and **Keylab** | BPC BioSede SRL | BPC BioSede SRL, 2009a<br>BPC BioSede SRL, 2009b |
| 2010 | USA | **Sesame** | Medical Murray | Medical Murray, 2011 |


***Figure 5.8.*** *Ultra Compact Hot Embossing Machine (see DTF, 2011), Desktop Nickel Plating Machine (ibid.), Nanomolding machine Sesame (Medical Murray, 2011)*

Medical Murray is a medical device engineering and manufacturing company form USA. In 2007, they published a nanomolding machine called Sesame. The machine is a floor standing but relative small when compared to other similar molding machines. With the machine, materials such as bioabsorbable polymers as well as thermoplastic and silicone rubber materials can be moulded. Applications include e.g. overmolded polymers, electronics or radiopaque markers. (Medical Murray, 2011)

In addition, multiple desktop-size automated laboratory devices have been developed, e.g. analysis systems (DYNEX Technologies, 2007a, 2007b) and chemistry analysers (BPC BioSede SRL, 2009a, 2009b). Unlike the Nexar® system above, these devices are designed mostly for stand-alone use.

Furthermore, small-size and stand-alone robotic cells have been developed for specific applications. In 2009 a Swiss company, Asyril, published their first table top cell, Asyfeed Pocket. The overall size of the cell is 400x400x500mm. It is a miniaturized version of the floor standing cell, Asyfeed Desktop (800x800x2250mm). The both include a PocketDelta Robot (highly miniaturized and high precision delta robot), an Asycube (flexible feeding system) and an Asyview (vision system). They are primary designed for sorting and palletizing of bulky micro-components. Work-cycles up to 3 components per second can be achieved. In addition, the cells can be modified to assembly and measurement tasks. (Asyril, 2010) In 2011, an improved version of Asyfeed Pocket was published. (Asyril, 2011a)

***Table 5.7.*** *Examples of commercialized small-size stand-alone robotic cells*

| | | | | |
|---|---|---|---|---|
| 2009 | CH | **Asyfeed Pocket** | Asyril | see Asyril, 2010 |
| 2010 | FIN | **J505-62** | JOT Automation | JOT Automation, 2010a |
| 2011 | FIN | **Roboline** | Biohit Oyj | Biohit, 2011a |
| 2011 | CH | **Asyfeed Pocket** | Asyril | Asyril, 2011a |

***Figure 5.9.*** *Asyfeed Pocket 2009 (Asyril, 2010), J505-62 (JOT Automation, 2010a), Roboline (Biohit, 2011a), Asyfeed Pocket 2011 (Asyril, 2011a)*

Similarly, JOT Automation has developed the J505-62 Desktop Robot Cell for Screw Insertion. The cell has dimensions of 495x754x962mm and it includes e.g. linear motor driven X and Y axes, two screwdrivers and a four index rotary table. Compatibility to Lean production is mentioned as well. (JOT Automation, 2010a)

Desktop-size robotic cells have been developed for non-manufacturing applications as well, e.g. for medical and bio industries. For example, Biohit is a Finnish company, specialized in liquid handling products, i.e. electronic and mechanical pipettes and disposable pipette tips. In 2011, Biohit launched the Roboline which is a desktop cell for automated pipetting. The unit has a size of 347x346x381mm and it weighs 11.5kg. (Biohit, 2011a) For more information, please refer to the sub-section 6.2.2.

### 5.3.3. Commercial miniaturized machining units

Since the millennium, multiple commercial small-size and stand-alone machining units has been developed (see Table 5.8 and Figure 5.10). For example, Japanese NANO Corporation published the Micro Turning System in 2002. The suitcase-style system has a base of 150x100mm and it includes a CNC precision lathe (Iijima, 2002). According to the author's knowledge, it has been one of the only commercial factory-in-a-suitcases. The miniature machining systems are designed for versatile materials and applications, e.g. metal (micro mechanics, jewellery and watches), glass (micro-optics), plastic (hearing aids), ceramics (dental) and biodegradables (implants).

***Table 5.8.*** *Examples of commercial small-size stand-alone machining units*

| Year | CC | Machine | Company | Source |
|---|---|---|---|---|
| 2002 | JP | **Nanowave MTS2** | Nano Corporation | Iijima, 2002;<br>Nano Co., 2005a |
| 2003 | JP | **Multi-Pro** | Takashima Sangyo Co. | see Endo, 2010;<br>Takashima Sangyo, 2011 |
| 2003 | JP | **Multi-function Turning Center** | DTF | see DTF, 2011 |
| 2004 | JP | **TRIDER-X** | Rinken Co. | Lin et al., 2004 |
| 2004 | JP | **Desktop Milling Machine** | PMT Co. | see Okazaki et al., 2004 |
| 2004 | JP | **Cylindrical cells** | SII Co. | see Okazaki et al., 2004 |
| 2005 | JP | **Nanowave MTS3**<br>**Nanowave MTS4**<br>**Nanowave MTS5/MTS6** | Nano Corporation | Nano Co., 2005b<br>Nano Co., 2005c<br>Nano Co., 2005d |
| 2008 | USA | **G4-ULTRA CNC** | Atometric Inc. | Atometric Inc., 2008 |
| 2008 | USA | **Microlution 363-S** | Microlution Inc. | Microlution Inc., 2007 |
| 2008 | USA | **EM203**<br>**GM703** | SmalTec | SmalTec, 2008a<br>SmalTec, 2008b |
| 2009 | USA | **MM903** | SmalTec | SmalTec, 2009 |
| 2009 | JP | **Micro mill CVN-2000** | Enomoto Kogyo | Enomoto Kogyo, 2009 |
| 2010 | GER | Impression line: **cam4-02**, **cam5-02**, **cam4-K1**, **cam4-K2** | vhf camfacture AG | vhf camfacture, 2010 |
| 2011 | FIN | **Kolibri** | Wegera | Wegera, 2011a |


***Figure 5.10.*** *Micro Turning System (Iijima, 2002), CAM 4-02 (VHF camfacture, 2011), Kolibri (Wegera, 2011b)*

Besides the industrial machines, some inexpensive and low-precision desktop machines have designed for hobby and educational use (see Table 5.9 and Figure 5.11). The iModela iM-01 is an affordable 3D hobby mill designed by Roland DG Corporation. The system has dimensions of 214x200x205mm and it weighs 1.7kg. The cells folds up and it can be packed in a suitcase. (Rolanda DG Co., 2011a) The prices vary between $500 and $5000. A Japanese company Originalmind has multiple low-priced machining units as well, e.g. the BLACKII 1510. It is an educational CNC machine with a base 150x100mm and a weight of 8.3kg. Prices start from $1279. (Originalmind, 2011)

***Table 5.9.*** *Examples of commercial small-size hobby and educational machining units*

| Year | CC | Machine | Company | Source |
|---|---|---|---|---|
| Since 1999 | USA | **CNC tools for hobbyists** | HobbyCNC | HobbyCNC, 2011 |
| 2010 | UK | E.g. **PRO II MDX-540E** and **RotoCAMM MDX-40AE** | Techsoft UK | TechSoft UK, 2010a TechSoft UK, 2010b |
| 2011 | JP | **iModeal iM-01** | Roland DG Corporation | Rolanda DG Co., 2011a; Rolanda DG Co., 2011b |
| 2011 | JP | Low-priced machining units, e.g. **BLACKII 1510** | Originalmind | Orginalmind, 2011 |

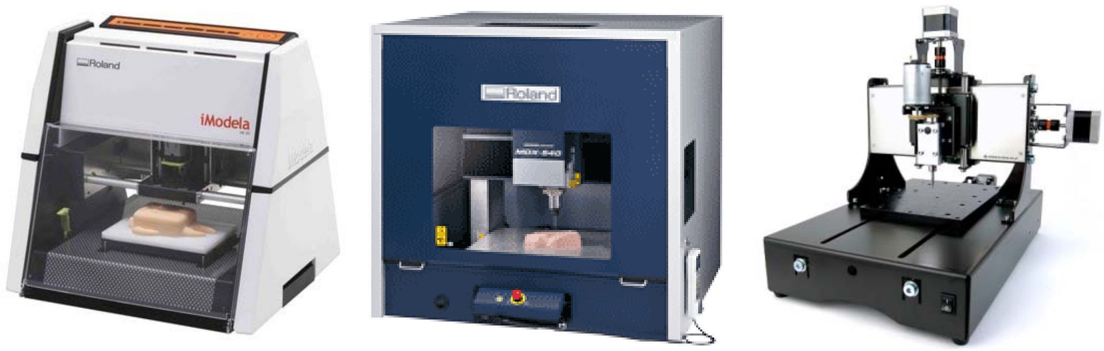


***Figure 5.11.*** *iModela iM-01 (Rolanda DG, 2011b), RotoCAMM MDX-40AE (Techsoft UK, 2010), BLACKII 1510 (Originalmind, 2010)*

Some companies are specialized only in educational machines, e.g. a British company Techsoft UK. They have from example models PRO II MDX-540E and RotoCAMM MDX-40AE, which are 3/4-axis educational CNC machines. The latter is slightly heavier and larger (1060x1100x978mm, 170kg) but they both can be place on a table. The prices start from $4695 and $13995. (Techsoft UK, 2010a, 2010b)

Besides the pre-assembled equipment, there are some construction-kit type CNC machines on the market, provided by e.g. American HobbyCNC. The kits start from $550 and the machines are usually built out of plywood or plastic. (HobbyCNC, 2011)

### 5.3.4. Commercial rapid prototyping units

In general, 3D printers can be used to e.g. proofing a concept, testing functionality of parts or demonstrating products for a customer. Recently 3D printers have started to shrink to a desktop-size as well (see Table 5.10 and Figure 5.12). Some well-known models include Dimension uPrint and uPrint plus (Dimension, 2010), Solido SD300 Pro (Solido LTD, 2009), 3D Systems V-Flash (3D Systems Inc., 2011b), Objet24 (Objet, 2010a) and Objet30 (Objet, 2010b). Weights of the printers vary between 45kg and 93kg. Respectively, dimensions vary between 160x210x135mm and 660x685x787mm. They cost between $10,000 and $40,000. The layer thickness varies between 0.028mm and 0.254mm. An American company Desktop Factory has been developeding an inexpensive desktop-size 3D printer, Desktop Factory 125ci. The printer has dimensions of 508x635x508 mm and it weights 50kg. The layer thickness is 0.254mm. Prices start from $4,995. (3D Systems Inc., 2011a) However, the printer has not been launched yet.

***Table 5.10.*** *Commercial small-size 3D printers and rapid prototyping units*

| Year | CC | 3D printer | Company | Source |
|---|---|---|---|---|
| 2009 | USA | **uPrint** and **uPrint plus** | Dimension (Stratasys) | Dimension, 2010 |
| 2009 | IL | **SD300 Pro** | Solido | Solido LTD, 2009 |
| 2009 | USA | **V-Flash** | 3D Systems | 3D Systems Inc., 2011b |
| 2010 | USA | **ModelMaker** | 2BOT physical Modeling Technologies | 2BOT physical Modeling Technologies, 2010 |
| 2010 | USA | **Objet24**<br>**Objet30** | Objet | Objet, 2010a<br>Objet, 2010b |
| 2011 | USA | **Objet260 Connex** | Objet | Objet, 2011 |
| 2012 | USA | **Desktop Factory 125ci** | Desktop Factory | 3D Systems Inc., 2011a |

***Figure 5.12.*** *ModelMaker (2BOT physical Modeling Technologies, 2010), Objet260 Connex (Objet, 2011), Desktop Factory 125ci (3D Systems Inc, 2011a)*

Some 3D printers can print parts from multiple materials. One of the smallest devices is the Objet260. The device can print up to up to 14 different materials into a single printed part. Over 60 materials are available. In addition, the device has eight printing heads and accuracy up to 16μm (depending on the material used). The printer is slightly larger, having dimensions of 870x735x1200mm and a weight of 264kg. (Objet, 2011) It is a bit over desktop-size but in a corner of an office it does fit into.

Besides additive 3D printers, other rapid prototyping units exist as well. For example, an American company 2Bot has and developed a subtraction-based rapid prototyping device, ModelMaker$^{TM}$. The unit has a cutter head and the models are made from high density foam. It is designed especially for educational use and prototyping. The dimensions of the unit are 635x635x330mm and the device can be plugged into a computer via USB. (2BOT physical Modeling Technologies, 2010) Although, subtraction places some restrictions, it could be useful e.g. for landscape architects.

Such as the educational machining units, some inexpensive and low-precision 3D printers have designed for hobby and educational use (see Table 5.11 and Figure 5.13). Both commercial products and open source based do-it-yourself machines exist.

***Table 5.11.*** *Examples of commercial desktop-size hobby and educational 3D printers*

| Year | CC | 3D printer | Company | Source |
| --- | --- | --- | --- | --- |
| 2006-2010 | UK | **RepRap 0.2**, **Darvin**, **Mendel**, **Huxley** and **Prusa Mendel** | RepRap (community project) | RepRap, 2011 |
| 2006, 2010 | USA | **Model 1** and **Model 2** | Fab@Home (community project) | Fab@Home, 2010 Fab@Home, 2011 |
| 2009, 2010 | USA | **CupCace CNC** (past) and **Thing-O-Matic CNC** | MakerBot | MakerBot, 2011 |
| 2009-2011 | UK | **RapMan 3.1** (past) and **3DTouch**, **RapMan 3.2** | Bits from Bytes | Bits From Bytes, 2011 |

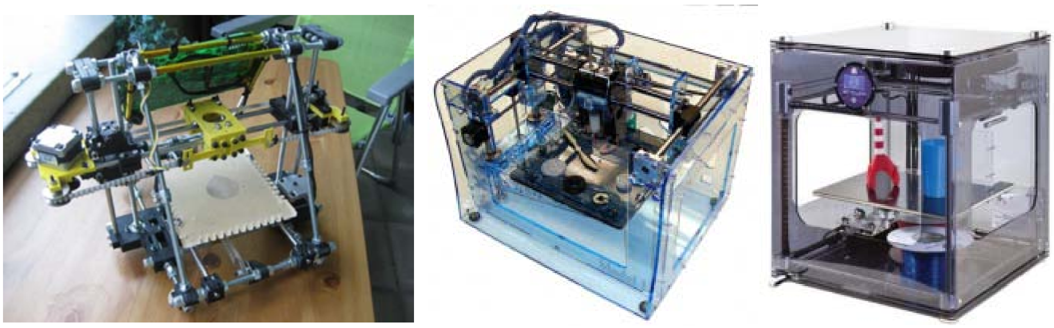

***Figure 5.13.*** *RepRap Huxley (RepRap, 2011), Fab@Home Model 2 (Fab@Home, 2011), 3D Touch (Bits from Bytes, 2011)*

The first open source 3D printer project was the RepRap, based on University of Bath in UK. It is a truly communal project. So far, four models have been developed: RepRap 0.2 (2006), Darvin (2008), Mendel (2009), Huxley (2010) and Prusa Mendel (2010). All the designs are open source; anybody can further develop them and publish online. One goal is that a 3D printer could be printed out of another 3D printer. One can either download the designs and print the parts itself or buy the parts from other members of the community. Price of a complete system varies between $400 and $650. All the models are desktop-size and lightweight. (RepRap, 2011) Another community based project is the Fab@Home, having more expensive and accurate printers than RepRap. The material is injected with two components. (Fab@Home, 2010, 2011).

Companies providing inexpensive 3D printers include e.g. MakerBot from Brooklyn and Bits from Bytes from UK. MakerBot have had two models CupCace CNC and Thing-O-Matic CNC. They are made out of plywood. CupCace CNC started from $649, but it is not on sale anymore. The price of Thing-O-Matic CNC varies between $1299 and $2500$. (MakerBot, 2011). The printers of Bits from Bytes are based on RepRap designs. Currently they have two models, RapMan 3.1 and 3DTouch. The former is a construction kit and the latter is a ready-made printer. Prices vary between $494 and $4015. (Bits from Bytes, 2011)

## 5.4. Observations from the interviews

Alain Codourey, the CEO of Asyril, made an interesting point of the microfactory development. He asked whether the idea of a microfactory really bases on the research conducted in Japan in the 1990's. Something similar did exist already centuries ago in the watchmaking industry. The original watchmaking tools, including e.g. lathes and mills, were also desktop-size units. In the early days, the machines were fully manual. The power was generated by a winch or a pedal. Later on, machine power was harnessed to spin the axis. The machines were still operated by small screws and arms. Later on, more motors and actuators were embedded to the machines. At the time, the motors were heavy and, a sturdy frame had to be embedded to the machines. Therefore, the machines got larger. Codourey points out that now the motors are finally smaller and the industry can return to the roots, manufacturing with desktop-size machines. (Codourey, 2011)

Christoph Hanisch (2011) notes that the structure of modular microfactories (q.v. 5.1.3 and 5.3.1) is not unique. For example Comau, a provider of automation for car factories, has a production cells with a similar structure like modular microfactories. The cells also have working space at front. The space at back is allocated for machines and the interfaces are standardized. However, car has as certain size and, therefore, the cell is also large. The cell has dimensions of 2x2x4m. (Hanisch, 2011)

Hanisch (2011) thinks that microfactory cells does not have to be as small as e.g. the TUT Microfactory concept is now. It depends on the size of the products. For many products, a bit bigger cells than microfactory could be used, being still much smaller than the ones in industry now. However, it is important to search the limit of miniaturization. Therefore, highly miniaturized academic concepts are needed (Hanisch, 2011). In fact, many other interviewees made similar annotations.

# 6. INDUSTRIAL CASES

In this chapter, nine different microfactory-related industrial cases are presented. Four principal cases (q.v. 6.1.1–6.1.4) relate to commercialization of microfactory research. Two following cases (q.v. 6.2.1–6.2.2) relate to development of small-size stand-alone automation and machining units. Three ultimate cases (q.v. 6.3.1–6.3.3) relate to different ways companies are using, or would like to use, micro and desktop production systems. All the cases, except one, are based on the interviews. The Takashima Sangyo case (q.v. 6.3.1) is based on literature (Endo, 2008).

## 6.1. Development of commercial systems based on research

In this section, four different commercialization cases are presented. Each of them presents a different way how industrial products can arise from the microfactory research. First, Percibio Robotics (q.v. 9.1.1) represents a traditional academic spin-off. It further developed a micromanipulation system, developed at FEMTO-ST, and made a product out of it. Asyril (q.v. 9.1.2) commercialized a miniaturized robot, based on research at HTI Biel, CSEM and EPFL. However, the actual commercialization was done by adaption of another company. μFemos and microFLEX (q.v. 9.1.3), instead, represent cases where products have been developed based on direct funding and co-operation between the industry and academics. Finally, MAG Lean (q.v. 9.1.4) is an example on how research can inspire and encourage companies to develop new products. All the cases are based on the interviews.

### 6.1.1. Percibio Robotics – An academic spin-off

Percibio Robotics is a young French start-up based on the research conducted at FEMTO-ST. The company is still under creation. (Percibio Robotics SA, 2011) The CEO of Percibio Robotics, David Hériban (2011), describes that Percibio Robotics designs and prototypes robotic systems for micro handling. The core product is a precise electrostatic gripper based on two piezo electric beams (see Figure 6.1, on the left). It is a mechanical gripper with a resolution of less than 100nm and a stroke of up to 2mm. Currently, the core business is to build specific solutions for the high-tech industry (e.g. electronics, biomedical and clockwork) based on customers' needs. (Hériban, 2011)

In addition, Hériban (2011) states that second business activity is under development. Percibio Robotics will build standard desktop robotic systems for clockwork assembly. A tele-operated desktop system is already under development (see Figure 6.1, FEMTO-

ST's old system on the right). The new system consists of two piezo electric grippers, robotic arms, a planary table, an integrated control software and 2 or 3 cameras. It is designed to work as a semi-automatic tool in the clockwork industry, for applications beyond capabilities of human hand. For example, precise assembly of axis might have accuracy requirement of 10µm. It is therefore very difficult with a pair of tweezers. Hériban believes that, in the future as well, there will be different levels of automation in the clockwork industry. Low-level automation is easy to configure and it can still save up to 90% of time. (Hériban, 2011)

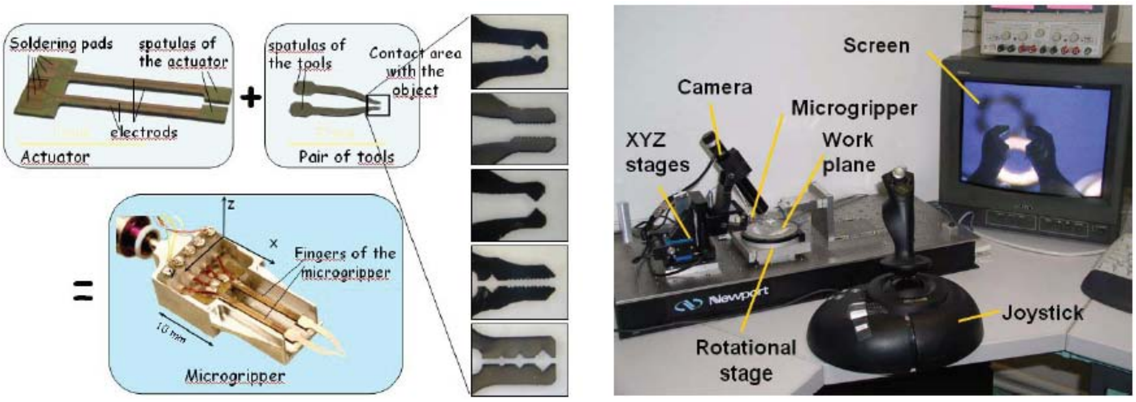


***Figure 6.1.*** *Micro-Assembly System developed by FEMTO-ST (Clévy et al., 2008)*

The beginning of the commercialization is interesting as well. According to Hériban (2010), Percibio Robotics aimed for the trendy MEMS industry in the beginning, as it was often referred within the academics. However, the companies in the industry were not highly interest of the new system. It turned out that the industry already has long-time (up to 20-year) technology roadmaps. The companies wanted to develop the old processes. The new system would have been too different. (Hériban, 2011)

Therefore, Percibio Robotics had to rethink the market and, luckily, good applications in the clockwork industry were found. Furthermore, Swiss clockwork industry is under revolution at the moment. The monopolistic production of the movements will finish in the end of 2012 and many companies need to setup their own production. Therefore, the market is extremely good at the moment. The robotic desktop cell will be presented in 2012. (Hériban, 2011)

### 6.1.2. Asyril – Commercialization through adaption

Asyril is a young Swiss company focussed on "the development of miniaturized mechatronic devices for automation in the fields of micro- and nano-technologies, biotechnologies and medicine". (Asyril, 2011b) The product line includes small delta robots, flexible feeder systems and robotic cells (see Figure 6.2) (Asyril, 2010). Asyril is based on the small delta robot, PocketDelta, which has an interesting history.


***Figure 6.2.*** *Examples of Asyril products – Asyfeed Desktop, DeskotopDelta, Asyfeed Pocket, PocketDelta, Asycube Messo and Asycube Forte (Asyril, 2011b)*

Codourey (2011) describes that in the beginning of the 2010 decade, there was a common microfactory project in Switzerland between EPFL (*École Polytechnique Fédérale de Lausanne*), CSEM (*Centre Suisse d'Electronique et de Microtechnique*) and HTI-Biel (*Hochschule für Technik und Informatik*). The Phd work of Irene Verettas at EPFL included the small microboxes with working space of 100x100x100mm (Verettas et al., 2005). The speciality of EPFL was the cleanrooms. At the time, Codourey was working at CSEM and he had co-operation with prof. Clavel. In addition, he was teaching robotics at HTI-Biel and he could suggest e.g. topics for student works. Therefore, few microbox-related student projects were launched. The topic of one student work was to develop a small robot enable to work in a small space. A student, Sebastian Perroud, researched different structures. As a result, delta structure was the most suitable for miaturization and it could be integrated into a cleanroom. In 2005, Perroud developed the first version of the PocketDelta. Then Codourey hired Perroud at CSEM to remake a miniaturized control cabined for the robot. (Codourey, 2011)

Codourey believed on the robot and searched funding to establish a company. As a result, he found CP Automation (CPA) in Villaz-St-Pierre, which wanted to widen their engineering know-how. In 2007, Codourey started to work at CPA. The task was to establish a new company. Codourey hided Sepastian Perroud and Jean-Babtiste Berset, and they worked nine months under CPA. In 1.10.2007 was the official start of Asyril. In the beginning they were not sure whether or not the miniaturized robot would sell. Therefore, they launched the PocketDelta as well as a larger robot, DesktopDelta. Finally, they found suitable applications in the watch industry and the robot started to sell. Nowadays Asyril has more than 22 employees. The start-up worked out well but it might be relative risky strategy. Nowadays, the development is more customer-oriented. Asyril focuses on developing equipment based on the customer needs. However, they do not want forget the innovativeness. (Codourey, 2011)

Codourey (2011) emphasizes that it is a rough road form the research into the industry. It takes a long time and a lot of capital to transfer a “nice research product” into a reliable and tested industrial product. The reliability is a combination of many things, e.g. testing, changing parts, checking and life time testing. In addition, one need the courage to change the product and own ideas to meet the customer requirements. Otherwise nobody might buy the product. Furthermore, Codourey confer that his opinion about miniaturization has changed during the commercialization. The industry understands the academic arguments of miniaturization, but they tend to ask what the real advantages are. The customers do not care if the robot is small or big. First of all, the robot has to solve customer’s problem. Beyond that, everything is secondary sales argument. Small size might benefit if there are equal products on the market. For example, PocketDelta sells because of speed and precision. However, energy saving is one argument the industry does understand and it might be more important argument in the future. Because of the lack of components Codourey believes it is better to enter the market nowadays in desktop-size, not really in micro-size. (Codourey, 2011)

***Table 6.1.*** *Examples of the applications of Asyril’s products (Codourey, 2011)*

| **Product** | **Industry** | **Applications e.g.** |
|---|---|---|
| DesktopDelta | • Watchmaking | • Palletizing (e.g. Tag Heuer has one) |
| PowerDelta | • Watchmaking<br>• Medical industry | • Weighting probes with a precision scale |
| PocketDelta | • Watchmaking<br>• Semiconductor<br>• (Tests for medical industry) | • Pick and place<br>• Palletizing (replacement for vibrating bowls together with Asycube) |
| Asycube feeder | • Watchmaking<br>• Medical industry | • Metallic, plastic, stone (in different fields)<br>• Feeding a medical machine |
| Asyfeed cells | • Watchmaking | • Palletizing (replacement for vibrating bowls)<br>• Other standard applications |

Codourey (2011) describes that, together with CPA, the products of Asyril can be sold both for end users and system integrators. Asyril sells the standardized desktop cells for the end customers, as well as robots and feeding devices for system integrators. In fact, Asyril is selling more desktop cells as there are not many system integrators as customers. In addition, CPA integrates Asyril’s products for special applications, e.g. systems with multiple manufacturing steps or gluing. The watchmaking industry is the largest industry for all the products. In addition, the medical and semiconductor industry have some applications (see Table 6.1). Applications include e.g. pick and place, palletizing and other standard applications. Furthermore, the customers prefer individual machines instead of lines. Asyril built a line out of PocketDelta robots only as a demonstrator in a mess. (Codourey, 2011)

### 6.1.3. µFemos & microFLEX – Cooperation

IEF Werner is a German company specialized in automation components and building machines for special purpose (IEF Werner, 2011). Two desktop factory concepts, µFemos and microFLEX, have been developed co-operation between IEF Werner, KIT (*Karlsruher Institut für Technologie*) and few other companies.

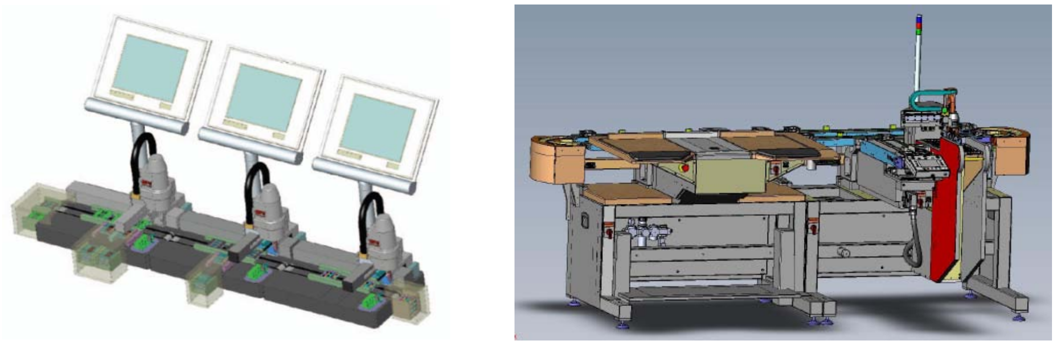

***Figure 6.3.*** *µFemos (Bär, 2006) and microFLEX (Hofmann et al., 2011)*

Andreas Hofmann (2011), a researcher of KIT, describes that the µFemos project lasted from 2003 to 2005. The participants changed a bit in the beginning. In the end, a German company wanted to develop an optical distant sensor with high precision. A research project was proposed for the assembly process of the sensor. IEF Werner designed the machine. KIT participated for assembly and logistical guidelines. As a result, the µFemos machine was designed (see Figure 6.3, on the left; Bär, 2006). µFemos includes a 4DOF high precision positioning system and a working space of 150x300x20mm. In the demonstration, multiple assembly operations were conducted in one cell. IEF Werner never sold the machine with that layout. However, the project taught a lot about high precision positioning units and piezo driven linear axis. Based on the knowledge, IEF Werner developed multiple commercial product lines, e.g. sensor positioning systems, components and piezo driven axis. (Hofmann, 2011)

Hofmann (2011) describes that the preparation and thinking of microFLEX concept started in 2007. The funded project lasted from 2009 autumn to 2011 august. The project was cooperation between IEF Werner, KIT and an anonymous industrial partner (a customer). In contrast to µFemos, the project was funded by German Ministry of Economics. Target of such projects is more or less to have a finished product in a catalogue. As a result, the microFLEX system was created. (see Figure 6.3, on the right; Hofmann et al., 2011) The units have dimensions of 1200x800x800m including 800x1000mm space for processes and in/out buffers. The logistics is based on 80mm trays and RFID tags. In addition, it is compatible with manual, semi-automatic and fully automatic production. Dimensions of the unit respond to the dimension of a manual assembly table in the industry.  KIT contributed about 20% of the development, mostly relating to tools, interfaces and logistics. Now the system is handed to the customer. IEF Werner has further developed and sold it to other customers. (Hofmann, 2011)

### 6.1.4. MAG Lean and JOT Lean cells – Research as forerunner

Master Automation Group (MAG) is a Finnish automation company providing intelligent and adaptive solutions for telecom, marine and aerospace industries (MAG, 2011). MAG has participated the TUT Microfactory projects since 2007 (see appendix 4). MAG has launched two generations of microfactory units (see Figure 6.4). The TUT Microfactory research encouraged the product development in the beginning.


***Figure 6.4.*** *The 1st generation of MAG Lean (Prusi et al., 2010), the 2nd generation of MAG Lean (MAG, 2010), JOT Lean assembly jig and JOT Lean (JOT Automation, 2011)*

According to a former engineer of MAG, Mika Laitinen (2011), the development of miniaturized production cells was mostly telecom based. In the first phase, a 500mm wide floor standing cell was developed for assembly processes and packing. The cell performed well but it was not competitive with Asian low-cost manual production. In the second phase, highly miniaturized desktop cells were developed. Targets included an A4 paper size footprint and cheaper price. It required new solution inspired by the TUT Microfactory projects. In the third phase, desktop cells were built out of commercial components. As a result, the first generation of MAG Lean cells was launched in 2010 (see Figure 6.4, two grey cells on the top). (Laitinen, 2011)

In 2011, the second generation of MAG Lean cells was launched (see Figure 6.4, two black and yellow cells on the top). Vesa Hirvonen (2011), the technology manager of MAG, agrees that MAG acted as an auditor of TUT in the beginning. Hirvonen describes that the cells have mostly users in the electronic and life science industries as well as within component manufacturers (e.g. in the automotive industry). Processes include screwing, precision assembly, plasma treatment, dispensing, marking and cleanroom processes. (Hirvonen, 2011) In the end of 2011, MAG merged together with another Finnish automation provider JOT Automation. New JOT Lean cells have already been launched (see Figure 6.4, below). They are further developed all-around, including e.g. better scalability of automation. (JOT Automation, 2011)

## 6.2. Development of commercial miniaturized stand-alone production machines and automation units

This section gives an insight into development of two miniaturized stand-alone production machines. Two selected case machines are Wegera Kolibri and Biohit Roboline™. Wegera Kolibri is an example of successful and commercialized in-house machine development. Biohit Roboline™ is an example of expanding automation into new non-manufacturing environments. The both cases are based on the interviews.

### 6.2.1. Wegera Kolibri – In-house machine development

Wegera is a Finnish subcontractor. The core business of Wegera is to mechanize and lathe metal and plastic, as well as manufacturing different assemblies. The company is established in 2001. (Wegera, 2011b) Wegera is specialized in small batches of components with average dimensions of a matchbox (Kauppi, 2011). In addition, Wegera has lauched a floor standing and small-size 3/5-axis CNC machining unit (see Figure 6.5). The 5-axis model includes XYZ axes, and a turning and rotating table (AC) (Wegera, 2011a). Currently, two sizes exist: 498x740x910mm and 748x740x910mm.

According to Seppo Kauppi (2011), the development of Kolibri started in 2006 within Wegera's production. Customers' products are usually small and they have complex shapes. Production with a 3-axis machine requires multiple set ups and attachments. There has been commercial 5-axis CNC machines for decades, but they are all relative large. As a result, Petri Lyyttinen, an employee of Wegera, made the first prototype of a small 5-axis CNC machine alongside with his job. The prototype was successful and Wegera started to further develop the machine for external markets. According to a market survey in 2008, smaller 5-axis machining units exist but none with a true CNC control and servomotors. The first machines were sold in 2011. (Kauppi, 2011)


***Figure 6.5.*** *Wegera Kolibri (Wegera, 2011b)*

Kauppi (2011) states, that Kolibri provides multiple advantages in comparison to traditional 3-axis CNC machines. For example, a small component with complex dimensions might need eight CNC programs and eight attachments with a 3-axis machine. However, only two CNC programs and two attachments are required with the 5-axis Kolibri. As a result, depending on the batch size, up to 36% cost savings can be achieved. In addition, the small size enables some new applications, in comparison to traditional large-scale 5-axis CNC machines. For example, Kolibri suites well for prototyping and educational use. It can be carried in through a normal double door, and it fits well in an office or a classroom. On the other hand, the small size enables capacity sales, as more machines can be placed at provider's premises. Wegera provides instant capacity for monthly charges as well. (Kauppi, 2011)

### 6.2.2. Biohit Roboline™ –Automation for non-manufacturing use

Biohit is a Finnish "globally operating biotechnology company that develops, manufactures and markets liquid handling products such as pipettes and pipette tips as well as diagnostic tests and analysis systems" (Biohit, 2010). In 2011, Biohit launched the Roboline™ (see Figure 6.6), a desktop cell for automated pipetting. The unit has a size of 347x346x381mm and it weighs 11.5kg (Biohit, 2011a).


***Figure 6.6.*** *Biohit Roboline (Biohit, 2011a)*

Kalle Härkönen (2011) estimates that there will be more similar devices on the market in the future. For example, large laboratory tests are converting more and more to point-of-care tests. Personalized implant manufacturing in a hospital represent the same point-of-care trend in the medical industry. Härkönen believes that health care and laboratory work is heading more and more to this direction. For example, England has been pioneer with the self-tests. Roboline™ might also include more options in the future, e.g. different pipettes and washing processes. (Härkönen, 2011)

However, Härkönen (2011) stresses that the medical industry is highly regulated and it can be challenging for traditional automation providers. For example, ISO 13485 certificate is required and the products require different validation and certification. In addition, it is vital to understand the industry and the application area. For instance, Biohit was not sure in the beginning for which applications Roboline™ was used. Therefore, the development became more laborious. At the moment, Roboline™ is designed mainly for researchers. All in all, Härkönen believes that desktops have more potential in research and laboratory use. Pharmacy requires too high volumes. Same applies for desktop-size micro cultivation; research and/or laboratory use might work but pharmacy probably not. (Härkönen, 2011)

## 6.3. Users and potential users of micro and desktop production systems

In this section, two users and one potential user of miniature production systems are presented. Examples in the first sub-sections, Takashima Sangyo and Nokia, are already using the technology in the production. In addition, Takashima Sangyo is designing and manufacturing the small-size machinery and equipment. Nokia, instead, is using the machines in production, but the use of desktop cells has evolved interestingly during the past years. Furthermore, Biohit would like to use desktops with certain processes. The case of Takashima Sangyo is the only case based on literature (Endo, 2008).

### 6.3.1. Takashima Sangyo – Small-batch microfabrication

Takashima Sangyo DTF Factory is based on miniaturized machinery (Endo, 2008):

1. 130 compact, lightweight and portable machines in 300m$^2$
   - Small-size machinery (e.g. NC microlathe and microlapping/ cutting)
   - MultiPro multifunction platform (e.g. laser processing, precision processing, EDM, jig grinder and up to 8-axis CAM system)
2. Takashima Sangyo is both a manufacturer and a provider of the machinery
   - Small-batch and small-volume production
   - Design and manufacture of the machinery and equipment

The Desktop Minkiro DTF Factory in Japan is one of the largest and most cited applications of micro and desktop factories. Takashima Sangyo is a Japanese company specialized in precision processing and space-saving technologies. The company has 220 employees and the business is divided into three lines: manufacture of precision machined parts, precision grinding/polishing and design and manufacture of machinery and equipment. (Takashima Sangyo, 2011) In other words, the company is both using and selling the small-size machinery.

Endo (2008) describes that the DTF Factory includes 130 compact, lightweight and portable machines in 300m$^2$ (see Figure 6.7). The factory is optimized for high-diversity and small-volume production which is, according to Endo, essential in Japan. The small-size machines enable flexible layout and production in lines, cells or batches. Both small-size machinery and multifunction platforms have been developed in-house. The small-size machinery includes e.g. microlapping machinery, a microcutter and a

NC microlathe. The multifunction machinery, MultiPro, can be used both as production equipment, as a positioning stage or as an accurate machining tool (q.v. 4.3.1). MultiPro can be modified into e.g. laser processing unit, precision processor, EDM machine, jig grinder and as 8-axis CAM system. (Endo, 2008)

***Figure 6.7.*** *Takashima Sangyo DTF factory (Endo, 2008)*

According to Endo (2008), compared to traditional production systems, energy saving is 50% to 80% per machine. The main advantage is the flexibility to handle different product variations. The layout of the DTF Factory can be changed within two hours line by line, by human power. In addition, the system is highly flexible for engineers and operators. For example, *kanban* control and visibility management are easily implemented. The miniaturization includes some drawbacks as well. The primary challenges relates to margins and the lack of commercial components. (Endo, 2008)

### 6.3.2. Nokia – Lean assembly of high-end mobile phones

The way Nokia uses desktop cells has evolved during past years (Zott, 2011):

1. The desktops were supposed to use as small-size production lines
    - The idea was abandoned because of flexibility requirements
2. Currently the cells are used for automated assisted assembly
    - Screwing, gluing and precision assembly: improving quality
3. Manual assembly with low and high level automation in the near future
    - High-level automation (desktops), low-level automation and humans

Nokia is a Finnish telecommunications corporation (Nokia, 2011). Jari Luotonen (2011) describes that Nokia's production is divided into high-end and mobile phone factories. In the high-end factories, Nokia is producing small quantities of high-end products. The products are produced in small batches based on orders. The production is divided into Lean production cells, having 2 to 3 persons and semi-automatic tools. Components are carried manually into the Lean cell. A typical factory serves from ten to one thousand customers. On the contrary, the mobile phone factories are based on twenty-four-seven mass production. The products do not vary much, only the colour might change. Both high-end and low-end production is mainly assembly of subcomponents, including only little automation. Automation is either inflexible or does not pay off with short life cycles. Nokia is using desktop cells in the high-end production. (Luotonen, 2011)

Andy Zott (2011) states that the way Nokia uses desktop cells has evolved during past years (see Figure 6.8). In the beginning, small automated assembly lines were designed out of desktop cells. The main motivation was floor-space reduction. However, the desktop lines were abandoned because flexibility requirements are too high. If a technology is flexible enough, it is too expensive. (Zott, 2011)

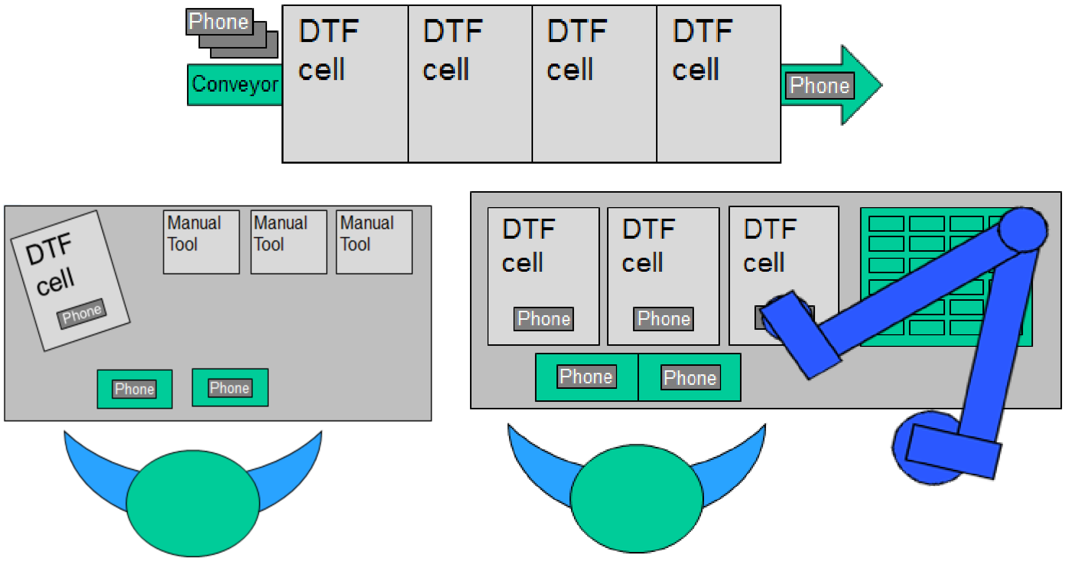


***Figure 6.8.*** *How desktops were supposed to use – A small-size production line (above), Current use – Automated assisted assembly (on the left), Near future – Manual assembly with low and high level automation (on the right)*

Zott (2011) describes that the desktop cells are currently used as a tools for assembly steps which cannot be conducted by humans. Human loads a cell and the cell conducts a specialized task. Desktop cells are used if manual assembly is not possible or difficult because of precision requirements. The co-operation between humans and automation suits also better to Lean which is contradictory to automation. The Lean cells have size of a small office room and they include 4 people and few desktop cells. (Zott, 2011)

According to Pykäri (2011), the desktop processes include screwing, gluing and precision assembly. For example, components might have small gaps at joints. If the component is glued exactly in the middle, the gap is as wide on every side and human eye does not see the difference. However, human operator would not be able to place it precise enough. The desktop-size has three primary benefits: it can be placed on a table in a relative small Lean manufacturing cell; one operator can use multiple desktop cells (i.e. savings on human resources); and it is portable and thus modular (i.e. it can be moved from a Lean manufacturing cell to another). However, the small size can be contradictory to flexibility, as e.g. maintainability and updateability might suffer from the small size and the design compromises. (Luotonen, 2011)

Zott (2011) describes that the next step might be to combine humans as well as low and high-level automation in the Lean cells. The desktop cells would be the high-level automation, used to replace time consuming, difficult and/or impossible manual assembly task. As stated above, the processes include e.g. precise pick-and-place, dispensing and screwing. The desktop cells would provide quality improvements to manual assembly. Manual assembly is extremely flexible and thus always needed. For example, operator has to attach manually flex cables of a screen before placing it into a desktop cell. Dispensing and exact adjustment occur in a desktop cell. In addition, a safety robot is tested for automated assisted assembly. It could operate next to a human operator replace the repetitive tasks, e.g. simple pick-and-place from trays and loading/unloading the desktop cells. The system is already under development. It might be in production within two years. (Zott, 2011)

### 6.3.3. Biohit – Lean production of liquid handling devices

Biohit would like to use desktop factories for (Härkönen, 2011):

1. Machining of injection moulded components on the spot
2. Automated assisted assembly (stand-alone units for Lean assembly)
3. Maybe some other applications in the future, e.g. final testing and packing

Kalle Härkönen (2011), states that Biohit's products can be divided into liquid handling products and diagnostic kits. Liquid handling devices include electronic pipettes, mechanical pipettes, pipette tips and automated pipetting units (q.v. 6.2.2, Roboline™). Diagnostic kits include quick tests and GastroPanel® kits. (Härkönen, 2011) Most of the products are handheld laboratory devices including micromechanics, electronics and plastic parts.

According to Härkönen (2011), the production process is mainly Lean assembly, except the production of disposable pipette tips which are produced in cleanrooms with fully automated mass production. The manufacturing process depends on a product. For example, the production process of high-end electronic includes roughly eight steps: 1. Fabrication and purchase of component (the plastic parts are injection moulded in-house, electronics and metallic precision mechanics are subcontracted). 2. Assembly of subassemblies in a fishbone layout (Just-In-Time production). 3. Assembly of the engine and gears. 4. Testing. 5. Marking serial numbers. 6. Final liquid testing (repeatability and accuracy). 7. Packing. 8. Shipping to a customer. (Härkönen, 2011)

Härkönen (2011) says that the interest in desktop factories is based on an own product (q.v. 6.2.2, Roboline™). There is a need for desktop factory units in the first and second assembly steps. First, they could be used to machining of injection moulded components on the spot, during the assembly. For example, some current mechanical and electronic pipettes include one very similar plastic component. The component of electronic pipette requires machining. Because of relative small batches, machining is difficult to outsource. Currently, injection moulding takes place in Vantaa and the components are send once a year to north of Finland, where they are machined. The process includes large stocks. Instead, the components could be machined during the assembly as well (Just-In-Time production). One worker could also operate multiple machines. Takt time planning and number of *kanban* provide tools for scheduling. Therefore, process time is not that critical. (Härkönen, 2011)

In addition, Härkönen (2011) describes that, in addition, desktop factory units could be used for flexible co-operation between humans and machines, including e.g. small 6 DOF safety robots. The goal is to eliminate repetitive working phases. Currently the Lean assembly includes only flexible tools, e.g. electric screw drivers. Desktop factory units minimize the safe areas. Therefore, workers and the robot(s) could work in as small area. In addition, cleanliness is important for new products. A dust-free ISO 8 class environment is needed for assembly of some of the components. Local cleanrooms could be one solution. (Härkönen, 2011)

Härkönen (2011) states that Biohit would like to participate the forthcoming TUT microfactory project. The two applications described above are the primary goals. In addition some other assembly phases, e.g. final liquid testing and packing could have applications for desktop factories. The production of disposable pipette tips is unlikely to have any desktop solution because of the huge volumes. However, some small-size and stand-alone test device could be usable to test the tips on-line. (Härkönen, 2011)

# 7. CHALLENGES AND ADVANTAGES OF MINIATURIZATION

In this chapter the primary challenges and advantages relating to miniaturization of production equipment are discussed. First, the section 7.1 summarizes the principal challenges. In the section 7.2, the advantages in the literature and supporting empirical evidence are discussed. The section 7.3 concludes the observations from the interviews. Finally, the section 7.4 fundamental reasons to invest on miniature production systems are presented.

## 7.1. Challenges of miniaturization

Miniaturization includes several challenges and drawbacks (see Table 7.1). Based on TUT's experience, subsystem (e.g. cameras, grippers and control systems) availability and price is one of the largest problems. As development require more in-house development, the system price increase and precision and/or reliability may suffer. System integration (e.g. wiring, mounting and sensor integration) becomes more difficult as well, which lead to e.g. indirect measurements. Micro environment itself and other physical restrictions of small equipment size cause some restrictions (e.g. sticky effect and sensitivity to vibration and power and/or force limitations).

***Table 7.1.*** *Conclusion of the challenges*

| Challenges | Results |
|---|---|
| **Subsystems availability and price**<br>• N.B. not of component but of subsystems (cameras, grippers, control systems etc.) | →System price increases<br>→Taylor component development (precision and reliability decreases) |
| **Difficult system integration**<br>• Difficult wiring and mounting<br>• Difficult sensor integration | → System price increases<br>→Indirect measuring (precision decreases) |
| **Physical restrictions of small equipment size**<br>• Smaller lever arms and pneumatic lines<br>• Relative mass of sensors and actuators<br>• Sensitivity to vibration and temperature | →Power and force limitations<br>→True ratio of moving mass/performance?<br>→Precision decreases |
| **Restrictions of micro environment**<br>• Gravity becomes insignificant, adhesion and other surface forces dominates instead | →Sticky effect (instead of e.g. vacuum grippers, more expensive and sophisticated grippers need to be bought or developed) |

As a result, price tends to decrease only to a certain point when scaling down machines, further it increases dramatically. In addition, precision and mass-performance ratio might not scale down as expected. The relative large subsystems effect on the mass-performance ratio. For example, a relative large vacuum gripper decreases performance of a mini robot more than a normal robot. Furthermore, in extremely small systems has space only for e.g. small lever arms and pneumatic lines, being less powerful. Force and power limitations might exclude some applications. In conclusion, a really small system requires other arguments than price.

## 7.2. Advantages of miniaturization by Okazaki

Based on the literature, multiple advantages are linked to miniature production systems. According to Okazaki (2010), the advantages can be categorized into four groups: ecological advantages, economic advantages, technical advantages and human advantages (Okazaki, 2010). The table below lists the advantages and relating to some empirical evidence (see Table 7.2).

***Table 7.2.*** *Conclusion of the advantages*

| Advantage | Significance | Empirical evidence |
|---|---|---|
| **1. Ecological advantages** | | Ashida et al. 2010 |
| A. Energy and recourse saving | +++ | Kaneko et al. 2010 |
| B. Reduced heat, vibration, noise and waste | ++ | Endo, 2010 |
| C. Local environmental control | **(?)** | Ecribano Gimeno, 2010 |
| **2. Economic advantages** | | Ashida et al. 2010 |
| A. Reduced running costs | + | Kaneko et al. 2010 |
| B. Efficient use of space | +++ | Barkley, 2009 |
| C. Improvement equipment portability | **(?)** | |
| D. Reconfigurability and scalability | +/- | |
| E. Agile ramp up | +/- | |
| F. Enchanged cell manufacturing | **(?)** | |
| **3. Technical and engineering aspect** | | Ashida et al. 2010 |
| A. Higher speed of reconfiguration | + | Barkley, 2009 |
| B. Precision because of small manipulators | – | Ogawa, 2010 |
| C. Productivity via parallel layout | + | Endo, 2010 |
| D. Piece-by-piece processing | ++ | |
| E. Process integration | + | |
| **4. Human aspect** | | |
| A. Easier recruiting (less stress etc.) | **(??)** | |
| B. Educational and non-expertise applications | **(?)** | |
| C. Human machine harmonization | ++ | |

In addition, the table includes author's estimation on the significance. To sup up, it appears that the energy saving and efficient use of space are the most significant advantages. However, it is not clear how much the small size cut costs, or how important is the size for companies in their use of the systems. The advantages are discussed more extensively in the following sub-sections.

### 7.2.1. Environmental advantages

Okazaki (2010) states that the ecological advantages include energy and recourse saving; reduced heat, vibration, noise and waste; and local environmental control (Okazaki, 2010). Kawahara et al. (1997) argue that the energy saving relates to the miniaturization factor. When the machines are miniaturized by factor 1/X, operation energy is evaluated to decrease by factor $1/X^3$. Similarly illuminating energy is supposed to increase by factor $1/(1.5 \times X^3)$ and air-conditioning by $1/(3 \times X^3)$. However, the required process energy will not change. Because the process energy corresponds to only approximately 8% of the total energy, miniaturization enables major potential for energy savings. (Kawahara et al., 1997) Ogawa (2010) states that the miniaturization saves operation energy because it includes less moving mass. (Ogawa, 2010)

The empirical evidence appears to support some of the ecological advantages. Ashida et al. (2010) designed a modular production system for MEMS production. In the case, environmental impact was reduced greatly because far less waste and toxin related to the production process. Traditional process included a lot of waste material, such as resists and process gases. The miniaturized process required only small amount of Nitrogen or Helium. Power consumption reduced by 1/45, from 360,000 to 8,000 kWh per year. (Ashida et al., 2010) Kaneko et al. (2010) miniaturized a CNC lathe. As a result, standby energy was decreased by 66% and process energy was decreased by 74%. The miniaturized system had similar performance than a traditional system. (Kaneko et al., 2010) Endo (2010) states, that Takashima Sangyo is able to save energy from 50% to 80% per machine (Endo, 2010).

Escribano Gimeno (2010) researched the use of operation energy of different manipulators. As a result, the smallest robot, CSEM PocketDelta, consumed up to 87 times less energy than the HISAC PMJ Assembly cell. The latter used 456.07J energy per cycle. Instead, PocketDelta used only 5.213J per cycle. HISAC had a power consumption of 614W, PocketDelta used only 8.5W. However, the cycle times were relative similar (0,660s vs. 0,612s). (Escribano Gimeno, 2010)

### 7.2.2. Economic advantages

Okazaki (2010) describes that the economic advantages include reduced running costs; efficient use of space; improvement equipment portability; reconfigurability and scalability; agile ramp up; and enhanced cell manufacturing. (Okazaki, 2010) Cutting and or machining time decrease because axes have smaller travels and tools are nearby, which fastens the setup time (Ogawa, 2010). Economic advantages are evaluated more precisely by prof. Jacot's team at EPFL (see e.g. Koelemeijer Chollet et al., 1999; 2003a; 2003b). The calculations are based on a similar logic than the energy saving by Kawahara et al. (1997). However, they based on an assumption that miniature production systems are used traditional production systems in production lines.

In addition, empirical evidence supports some of the economic advantages stated by Okazaki (2010). Ashida et al. (2010) states that the modular and miniaturized MEMS production system decreased floor space requirements by 1/30 to 1/100, depending on method of calculation. The miniaturized system required only 10m$^2$ floor space. In the beginning, the system required 300m$^2$. However, with incidentals, the total area was 1000m$^2$. Process time decreased from 1.2min–12min per wafer to 1min per wafer, depending on batch size. Small batches favoured more the miniaturized system. (Ashida et al., 2010) Barkley (2009) describes that the Mobile Parts Hospitals (MPHs) of US Army can decrease delivery time of replacement parts from 60 days to few days because they can be produced on location (Barkley, 2009).

### 7.2.3. Technical advantages

According to Okazaki (2010), the technical and engineering advantages include higher speed of reconfiguration; precision because of small manipulators; productivity via parallel layout; piece-by-piece processing; and higher level of process integration. (Okazaki, 2010) The author argues, that some of the advantages does not relate directly to the small size of the equipment. For example, piece-by-piece processing instead of batch processes is more a general goal of the research, not an advantage.

However, some empirical evidence supports the speed of reconfiguration and process integration. Ashida et al. (2010) state that the amount of manufacturing steps decreased from 20 to five in the miniaturized MEMS production system (Ashida et al., 2010) Ogawa (2010) describes that the compact machining center weights 400kg. However, it has wheels and it is therefore moved by human power. As a result, the production layout can be changed easily. (Ogawa, 2010) Endo (2010) states, that Takashima Sangyo DTF Factory supports better small-volume production and short life cycles. Normally, changes in layout would take few days. The production would have to be stopped and the changes would require cranes and/or rewiring. Instead the DTF Factory can be changed within 2h production line by production line. In addition, the system enables easy visibility and fast kanban control. (Endo, 2010)

### 7.2.4. Human advantages

According to Okazaki (2010), the human advantages include easier recruiting; educational and non-expertise applications; and human machine harmonization. Recruiting becomes easier, because the work becomes less hard, dirty and dangerous. (Okazaki, 2010) According to author’s knowledge, no empirical evidence refers to the recruitment advantage. In addition, in author’s point of view, the educational and non-expertise applications are applications, not advantages, of miniature production systems. Human machine harmonization is a major advantage instead. According to the interviews, the desktop factories are used nowadays mainly as a tool for component manufacturing and assembly processes. In the way many companies tend to produce (q.v. 9.3), the co-operation between humans and machines is a benefit.

## 7.3. Observations from the interviews

This section discusses some of the advantages and disadvantages cited in the interviews. Frist, the sub-section 7.3.1 discusses the advantages of miniaturization. Second the sub-section 7.3.2 discusses the challenges.

### 7.3.1. Advantages

Mika Laitinen (2011) states an interesting advantage of miniaturization: the equipment is easily dispensable because of the small size. For example, the telecom industry is a “large-scale consumer” of automation. The modification of the production equipment does not always work. Products have extremely short life cycles and the production equipment might become outdated with new product generations. It is easier to invest in new machines. As a result, a lot of electronic and mechanic junk is produced. As the machines are small, the old machines can be disposed easily or placed e.g. on a bookshelf. In addition, disposing and recycling are cheap. On the other hand, far less material is needed to build a production process. (Laitinen, 2011)

Jari Luotonen (2011) states that three principal advantages relate to the desktop cells Nokia is using. First, the Lean production cells are relative small. Desktop cells fit into the Lean cell and they can be placed on a table. Second, one operator can use multiple desktop cells in a small space, which decreases human recourse costs. Third, modularity is achieved through portability of the desktop cells. A stand-alone desktop cell can be carried to another Lean production cell and it works instantly. (Luotonen, 2011) Andy Zott (2011) adds that the small floor space is important indeed if the factory is full. In general, the floor space is relative cheap, even with all the fixed costs. However, acquiring new space includes huge step costs and Nokia does not want to build more production facilities. (Zott, 2011) Christoph Hanisch (2011) and Vesa Hirvonen (2011) cite the fact as well. Companies usually prefer not to build more facilities. The production equipment has to fit mainly into the current premises.

Also other interviewees brought up the advantage that microfactories can work flexibly in cooperation with human. Vesa Hirvonen (2011) stated that the components are becoming smaller and smaller. The accuracy of manual assembly is not enough anymore. In addition, microfactories can isolate dangerous processes. (Hirvonen, 2011) According to Christoph Hanisch (2011), the efficiency can be also enhanced with the human-machine cooperation. (Hanisch, 2011)

The energy saving was another clear advantage which was cited in many interviews. Andreas Hofmann (2011) states that energy saving is an important aspect and it will be likely more important in the future. At the moment, a lot of energy gets wasted e.g. by moving 2x2x1mm parts 10-15cm with a machine of one cubic meter and 15cm thick granite base. (Hofmann, 2011) According to Alain Codourey (2011), the industry understands the academic arguments and advantages. However, they tend to ask what the real benefits are. The small size is usually only a secondary sales argument. However, energy saving is an exception the customers understand. (Codourey, 2011)

Philipp Kobel (2011) states, that the microfactories and local cleanrooms can enable cleanroom production for smaller enterprises. Cleanrooms are becoming more and more expensive. In average, it is 250% more expensive to build a cleanroom than 10 years ago. It is because the cleanrooms are cleaner and more complex than before. The machinery inside a cleanroom becomes also more expensive because the requirements are higher. As a result, smaller companies can't effort an own cleanroom. (Kobel, 2011)

### 7.3.2. Disadvantages

Also different disadvantages and drawbacks relating to miniaturization came up in the interviews. According to Mika Laitinen (2011), few problems relates to the business. It is possible to develop a low cost automation cell. However, the development remains as expensive. In fact, the development costs usually increase in relation to total costs. The same applies for the users. The equipment might be less expensive but the ramp-up effort remains the same. In addition, the equipment is rarely as flexible as expected. Educated employees are still needed to set up and use the machines. Automation still requires repetition. Furthermore, in-house development includes a business risk. On the one hand, small amount of order does not generate enough profits. On the other hand, large amount of orders includes a risk of bad quality. If one component breaks down, all the machines around the world have to be replaced or fixed. (Laitinen, 2011)

Jari Luotonen (2011) states that the small size can be sometimes contradictory to flexibility and maintainability. As machines are highly miniaturized, the electronics and other control systems can be scattered around the body. Changing of a single component might require e.g. dismantling and recalibration of the machine vision system. In traditional machines, the systems are placed tidily in separate location and it is easier to maintain them. In addition, flexible microfactory lines might not be as flexible as expected. For example, programming and robustness causes problems. (Luotonen, 2011) Andy Zott (2011) explains that the desktop lines were abandoned because flexibility requirements were too high. If a technology is flexible enough, it is usually too expensive. (Zott, 2011) The same phenomenon has been noticed also at Asyril. Alain Codourey (2011) states that, the customers prefer individual machines instead of production lines. Asyril built a line out of PocketDelta robots only as a demonstrator in a mess. The customers do not want to buy lines. (Codourey, 2011)

In addition, the physical restrictions were cited. Both Cristoph Hanisch (2011) and Jukka Kenttämies (2011) describe that force and power limitations might exclude some microfactory applications. In addition, Kenttämies states that the extremely small component requirements are usually based on restricted design. For example, a machine is designed with certain dimension and strokes. Besides the actual stroke, an axis requires e.g. extra length for acceleration and deceleration. (Kenttämies, 2011)

## 7.4. Fundamental reasons to invest in miniature production technology

In this thesis, the advantages of miniaturization are linked to four primary reasons to investment in miniature production systems (see Table 7.3). In reality, companies have multiple options for any investments on production equipment (see chapter 4). Of course, the miniaturized system is bought if there are multiple solutions for a given production process on the market and the small system is a better for the application. However, the miniaturized system is likely to be more expensive or a compromise in some way. Therefore, the investment requires other motivation.

***Table 7.2.*** *Reasons to invest in miniature production systems (based on Tuokko & Nurmi, 2011)*

| **Reason** | **Direct Benefit** | **Indirect benefit** |
|---|---|---|
| **1. Enabling production** | • **No space for traditional equipment**<br>• **Industrial products are not available**<br>- Difficult logistics<br>- Time of delivery | |
| **2. Enabling product characteristics** | • Producing perishable products on the way<br>• Fragile products (small forces)<br>• (Accuracy/precision is rarely the case) | |
| **3. Improving profitability**<br>A. Cost savings* | • **Cleanroom investment/ maintenance**<br>• **Costs of energy**<br>• Costs of flexibility<br>• Costs of poor quality<br>• Costs of facilities<br>- Rents or capital costs, heating, air conditioning, illumination etc.<br>• Costs of material<br>• Costs of waste and recycling<br>• Capital costs of stocks (set-up/cycle times) | • Capital costs<br>- If investors think the technology is "greener" and value it (lower interests rate) |
| **3. Improving profitability**<br>B. Add-on sales or increasing efficiency | • **Increasing efficiency or quality through automated assisted manufacturing**<br>• Add-on sales<br>- If customers buy the product because of personalization or faster delivery | • Add-on sales<br>- If buyers think the technology is "greener" and value it |
| **4. Other** | • Employee welfare (e.g. noise, vibration) and sustainable development (e.g. waste)<br>- Without marketing purposes | |

* Depending on use; (Koelemeijer Chollet et al., 1999; 2003a; 2003b) in some occasions

First, microfactories might enable the production on the spot, in case there is no space (e.g. urban factory, laboratories and production inside of laboratory devices) or factory products are needed but not available (e.g. spare part production in battlefield or in the Third World). In addition, logistics might be difficult or delivery would take too long. Second, microfactories might enable the product or some of the product features, e.g. fragile products which are not destroyed by small forces, and perishable products could be fabricated on the way. The precision and accuracy of small actuators are stated in some papers but it appears that small system is always more sensitive for external factors and the practical issues decrease accuracy.

Third, microfactories might improve profitability by cutting costs or providing more with the same input. On the one hand, microfactories might decrease e.g. costs of recourses, costs of waste and recycling, as well as capital costs. On the other hand, microfactories might provide more with the same input, as they increase efficiency and quality of manual production. In addition, capital costs might decrease if the technology creates green image for the company. As a result, the company interest more investors, interests decrease and the capital costs decrease as well. Similarly, green image might help the company to sell more products on the market. However, the latter two factors are highly speculative.

Fourth group relates to soft values e.g. employee welfare (e.g. noise and vibration in the factories) and ecological values (e.g. energy consumption), which might be separate goals for a CEO or an owner of a company. However, if the object is only green marketing or cost savings, the third and fourth category overlap. To sum up, the primary reasons to invest in miniature production systems relate to different costs. In some cases they might enable the whole production.

# 8. APPLICATIONS

In this chapter, the applications of micro and desktop production systems are discussed. In the literature, there are a broad range of speculated applications for micro and desktop factories. In this thesis the different applications were gathered up and categorized by a supply chain. The framework (see Figure 8.1 and appendix 1 for large version) was build based on the applications and their benefits.The use of microfactories is categorized into three principal scenarios: miniaturization of production equipment in a traditional production chain (*I, q.v. 8.2*), relocating production further into the downstream (*II, q.v. 8.3*) and production on the spot (*III, q.v. 8.4*).

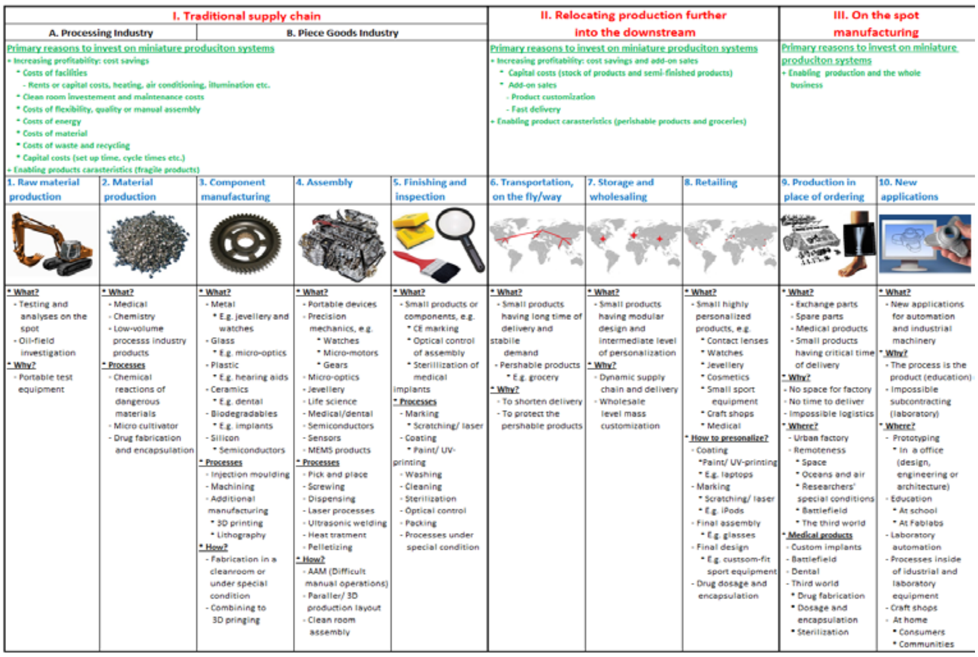


***Figure 8.1.*** *Applications for micro and desktop production systems, see large version in the appendix 1*

Traditionally the products are produced in factories and they are used somewhere else. If microfactories were used just to replace the large-scale production equipment, it is the scenario *I*. If microfactories were used to produce something in the place of use, it is the scenario *III*. Everything else, between the factories and consumption, including the point of purchase, is the scenario *II*. It does not matter how many companies relate to the supply chain, the benefits are still more or less the same. In addition, micro and desktop factories can be used for different levels of automation, from manual production to fully automatic lines. The levels of automation are discussed in section 8.1. The section 8.5 concludes the observations from the interviews. In addition, a roadmap of the possible applications is built up in the section 8.6.

## 8.1. Scalability of automation

According to Duncheon (2002), miniature products require different automation strategy than traditional products. The paper discusses mainly manufacturing of MEMS products and fiber optic components which are too small to be assembled and tested with human operators. Duncheon states that key components of automation for highly miniaturized products include designing the process manually first, using 3D simulation tools, implementing design for automation (DFA) processes, as well as using equipment with flexible and standardized components. In addition, the adaption of automation includes different phases (see list below). (Duncheon, 2002)

Levels of automation (based on Duncheon, 2002, p.18)

1. Manual (e.g. traditional watchmaking)
2. Semi-automatic
    - A. Automatic Alignment (q.v. 6.1.1, Percibio Robotics' cell)
    - B. Automatic Process (q.v. 6.3.2, Nokia's current use of desktops)
    - C. Automated Batches (q.v. 6.3.2, Nokia's future use of desktops)
3. Automatic
    - A. Robotic material handling (Asyril, 2011, JOT Automation, 2010a)
    - B. Automated Inter-Cell Transfer
        - i. Offline 'lines' (e.g. optical lamination in multiple phases)
        - ii. Fully automated logistic system (e.g. Hofmann et al., 2011)

The classification above applies not only for MEMS products and fiber optic components, but also for any small products to be produced in micro and desktop factories. Because of the small size, micro and desktop factories can be used for flexible human-machine cooperation. The different automation levels apply for most of the applications discussed in the following sections. First of all, small products can be produced manually by simple and flexible electronic tools. In Figure 8.2 above, an example of a simplified assembly task is presented. Currently, it is the case e.g. at Suunto (Suominen, 2011) and Vaisala (Pietari, 2011). The new products of JOT Automation emphasize the scalability of automation. For example, the Poka-Yoke assembly jigs can be used to increase efficiency and quality (JOT Automation, 2010b). The production is still manual, but the jigs prevent human errors.

To improve efficiency and quality of manual production, for example, tele-operated desktop factory units can be used (see 6.1.1 and Figure 8.2, the second row on the left). Even though the manipulation is tele-operated, automation of simple and repetitive tasks can save up to 90% of time (Hériban, 2011). The second step of automation is to automatize the whole process. An operator feeds the product and the components and the desktop cell conducts a given process (see 6.3.2-6.3.3 and Figure 8.2, the second row on the left). The same process automation can be applied for batches as well (see Figure 8.2, the third row on the left). Here, the operator feeds multiple products and/or components and the desktop cell applies the process for a small batch. It is a combination of Duncheon's 2C and 3A levels of automation (Duncheon, 2002). However, part feeding, e.g. large trays, can be a problem. Nokia is trying to round the problem by using large-scale safety robots to complement the desktop automation. (see 6.3.2 and Figure 8.2, the third row on the left)

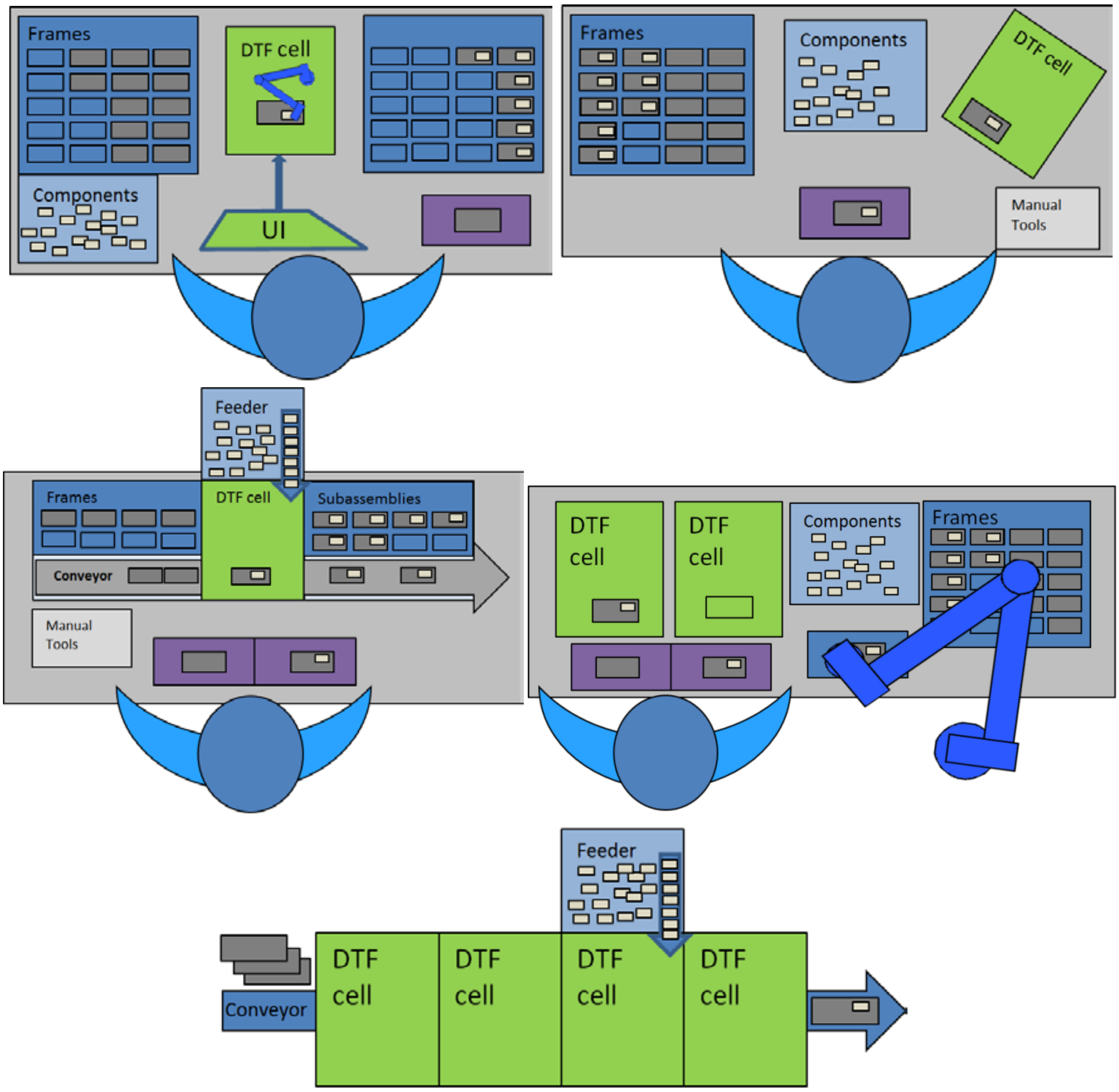


***Figure 8.2.*** *Human-machine cooperation (see Appendix 2):*
*Tele-operated desktop factory unit – Automatic alignment (the second row on the left),*
*Automated assisted assembly – Automatic process (the second row on the right),*
*Two different scenarios of small batch automation (the third row),*
*Multiple cells as offline process – Automated Inter-Cell Transfer (below)*

Finally, automated inter-cell transfer can be applied to few cells or to complete factory logistics system (e.g. Järvenpää et al., 2009, 2010). In the former case, the operator is using the cells as an offline process. The process is just divided into few cells (e.g. optical lamination). It should be noted that all the industries might not want complex and fully automated logistic systems build on microfactory modules.

## 8.2. Applications in a traditional production chain

The first scenario takes place in a traditional production chain. The traditional and large-scale production machines could be replaced with the micro and desktop production systems. Here, the production process remains the same. The production chain is divided into five phases: raw material production, material production, component manufacturing, assembly, and finishing and inspection. First two phases relate to processing industries, and the three latter phases relate to piece goods industries.

The products and processes, describes in the sub-sections 8.2.1 – 8.2.5, are examples of possible applications for microfactories. In general, all products and processes, which fit into the reduced working space, could be produced with a microfactory. However, it does not mean that small machines were needed or that the miniaturization was feasible. There is usually large-scale machinery for any given process. A desktop machine or a factory is bought instead if it's better for the application. As stated in the chapter 4, return requirements of investments depend on the purpose. If the large-scale machinery is replaced with the small machines in order to cut costs, the investment has to yield e.g. 15% annually. Interestingly, some machines tend to increase in size as they enter the market, because of other requirements. For example, Kaneko (2010) describes that Takamatsu Machinery Co. developed a lathe of 300mm in width. However, market required for more tools and dual spindles. Therefore, the spindle widened first to 480mm and then to 1000mm. (Kaneko et al., 2010)


***Figure 8.3.*** *Reducing the length of an assembly line (Klemd, 2007)*

The reasons to invest on miniature production systems, relate primarily to different costs. The profitability enhances if some costs decrease and output remains the same. By definition, micro and desktop factories are small. Therefore they can save space (see Figure 8.3). Thus, they can cut costs of facilities, e.g. rents or capital costs (own factory), as well as costs of heating, air conditioning and illumination. Similarly, microfactories use less energy which cuts costs of energy. Local cleanrooms can decrease cleanroom investments and cut maintenance costs. In addition, microfactories are expected to save material. Therefore, the costs of material, waste and recycling would decrease. With automated assisted manufacturing, microfactories could enhance quality of products. Therefore costs of poor quality would decrease. Finally, microfactories are expected to be more flexible, having shorter set up times. The flexibility would also cut the capital costs as cycle times are shorter and less stock, of products and semi-finished products, is needed.

The cost reduction factors have been discussed in the literature (e.g. Koelemeijer Chollet et al. 1999; 2003a; 2003b). The advantages are discussed in detail in the chapter 7. In addition, microfactories might enable some product characteristics or the product itself. For example, small-size machinery and grippers might prevent fragile products.

### 8.2.1. Raw material investigation and analyses

Microfactories relating to raw material investigation and analyses have been speculated. Kawahara et al. (1997) categorize microfactory systems in fabrication by desktop factory and fabrication by small robots. The latter include portable robots which could be used e.g. for water purifying and collecting of spilled oil, as well as mole-like robots which could be used e.g. oil-field investigation. (Kawahara et al., 1997) Even though fabrication by small robots goes beyond the scope of the thesis, the same idea could be applied to micro and desktop factories. As the equipment is small and portable, testing and analyses could be automated on the spot. The portable automation/testing equipment could be carried easily everywhere. However, applications relating to raw material production will probably not be the first microfactory applications.

### 8.2.2. Material production and process industry

In addition, Kawahara et al. (1997) argue that micro and desktop factories could be used as a micro chemical plant. Applications include e.g. drug fabrication, micro cultivating and chemical reaction of dangerous materials. Multiple benefits relate to the small reaction space. The reaction starts and ends quickly. Thus, risky exothermic reaction can be safely achieved. In addition, truly homogeneous chemical reaction becomes possible as the concentration differences decrease. (Kawahara et al., 1997)

In addition, the micro chemical plant could be used for other processes in the medical industry, e.g. for drug encapsulation. Possible industries include medical, chemical and other process industries. As described in the sub-section 5.3.2, multiple desktop-size automated analysing devices have been developed for laboratory use, e.g. automated analysis systems (DYNEX Technologies, 2007a, 2007b) and chemistry analysers (BPC BioSede SRL, 2009a, 2009b). However, the micro chemical plant could enable some unwanted and/or negative applications as well, e.g. illegal drug fabrication. The portable plants could be placed close to raw material resources, and the small size would benefit someone who prefer not be found. Actions should be taken to prevent such applications.

### 8.2.3. Component manufacturing

This sub-section describes applications mainly for machines such the ones presented in the sub-section 5.1.2 and 5.3.3. Component and micropart manufacturing was one of the original applications for microfactories. In general, they could be used to manufacture any small components which fit into the reduced working space. The benefits relate mostly to floor space reduction and relating costs. In addition, the small size machining units enable few additional business models for the equipment providers and subcontractors (q.v. 9.2). In addition, the small machines can support Lean and Just-In-Time production as components can be produced on the spot based on requirements. The small components are made of multiple materials (see Table 8.1): metal (e.g. jewellery, gears and watches), glass (e.g. microscopes, laboratory instruments and contact lenses), plastic (e.g. hearing aids and implants), ceramics (e.g. dental products and moulds), biodegradables (e.g. implants) and silicon (semiconductors e.g. sensors).

***Table 8.1.*** *Examples of small components suitable for microfactories*

| **Material** | **Component for e.g.** | **Source e.g.** |
|---|---|---|
| Metal | • Jewellery<br>• Gears<br>• Watches | Uhmori et al., 2010<br>Järvenpää et al., 2010 |
| Glass | • Micro-optics<br>• Microscopes<br>• Laboratory instruments<br>• Contact lenses | Ohmori & Uehara, 2010;<br>Ehmann et al., 2005<br>Michaeli et al., 2007 |
| Plastic | • Hearing aids<br>• Implants | Heikkilä et al., 2008<br>Medical Murray, 2011 |
| Ceramics | • Dental products<br>• Dental molds | vhf camfacture, 2010 |
| Biodegradables | • Implants | Tuominen, 2007 |
| Silicon | • Semiconductors (e.g. sensors) | |

Potential miniaturized processes include e.g. injection moulding (e.g. Michaeli et al., 2007; Medical Murray, 2011), machining (q.v. 5.1.2 and 5.3.3) and additive manufacturing, including 3D printing (q.v. 5.3.4) and lithography. In addition, components can be fabricated in a cleanroom or under special condition (e.g. Kawahara et al., 1997; Verettas et al., 2005; Kobel & Clavel, 2010). Furthermore, miniaturized machining could be combined to 3D printing for more precise products.

### 8.2.4. Assembly operations

Assembly operations are other promising applications for microfactories. Similar, to component manufacturing, any small products could be assembled in microfactories. The only restriction is that they should fit into the reduced working space. Suitable small-size products include e.g. portable electronic devices (MAG, 2011; JOT Automation, 2011), precision mechanics (e.g. watches, micro-motors and planetary gearheads) (Uusitalo et al., 2004; Järvenpää et al., 2010; CSEM, 2007), micro-optics, life science products (e.g. test kits) and other small medical products, dental products, semiconductors, sensors and measuring devices as well as other MEMS products (Ashida et al., 2010). Suitable miniaturized assembly processes include e.g. pick and place, screwing, dispensing, ultrasonic welding (MAG, 2011; JOT Automation, 2011) as well as palletizing (Asyril, 2011a).

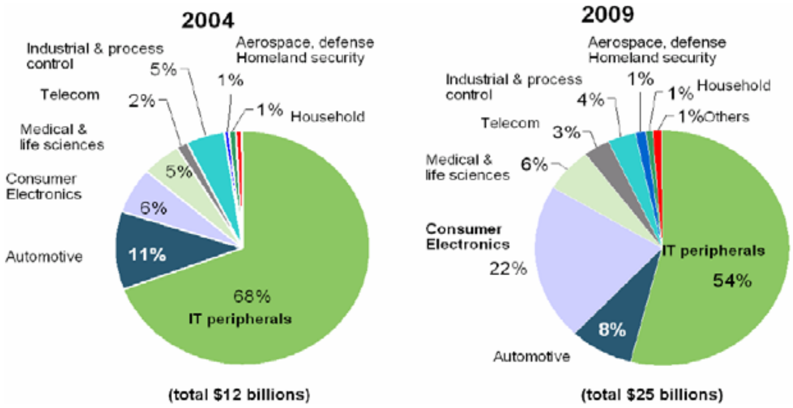


***Figure 8.4.*** *Microsystem market (NEXUS 2009, according to MINAM, 2008, p.5)*

In many cases, MEMS products (Micro Electro Mechanical Systems) are stated as potential products to be assembled with miniature production systems. (e.g. Aoyama, 2005; Ashida et al., 2010; Okazaki 2010, p.86) Walravel (2003) categorizes MEMS components into six different applications: sensors (e.g. airbag sensor, air quality and trace chemical analysis), actuators (e.g. electrostatic actuators), RF MEMS (e.g. metal-contact signal switches), optical MEMS (e.g. micomirros and fiber-optics), microfluidic MEMS (e.g. valves, pumps, and ink jet delivery systems) and bio MEMS (e.g. micro dialysis, biosensors, and laboratory analysis on a chip). Some of the most common applications include airbag acceleration sensors and print heads. (Walraven, 2003) In 2009 (see Figure 8.4), the largest markets segments for microsystem markets were IT peripherals and consumer electronics (NEXUS 2009, see MINAM, 2008 p.5).

In addition, to traditional assembly layout and automatic step-by-step assembly processes, microfactories could be used for automated assisted manufacturing (replacing difficult manual operations) (Kitahara et al., 1998), products could be assembled in local cleanrooms (Verettas et al., 2005; Kobel & Clavel, 2010) and the layout could include e.g. parallel machine allocation (Okazaki, 2010) and 3D structures.

### 8.2.5. Finishing, inspection and packing

In a traditional production chain, the last process is usually finishing, inspection or packing. Microfactories could be used e.g. for CE marking, optical control of assembly or sterilization of small medical implants. Other miniaturized processes include e.g.

marking, laser carving (Heikkilä et al., 2010, p. 121), painting, UV-printing (Tirkkonen, 2011), ultrasonic washing (Heikkilä et al., 2008), cleaning, sterilization and packing. In addition, a microfactory with a cleanroom enables processes under special conditions. Again, the only restriction is that the small products and components have to fit into the working space. According to Madou and Irvine, Sankyo Seiki made the first commercial equipment for cleaning of micro-parts (Madou & Irvine, 2005).

## 8.3. Relocating production further into the downstream

The second scenario is relocating production further into the downstream. By smaller machinery, some production steps could be relocated to three different phases between a factory and a customer (see Figure 8.5). Fist, the products could be produced on the way, e.g. on a boat or in an aeroplane. Second, the products could be personalized at wholesaling level. Third, the personalization could be placed at retailing level.

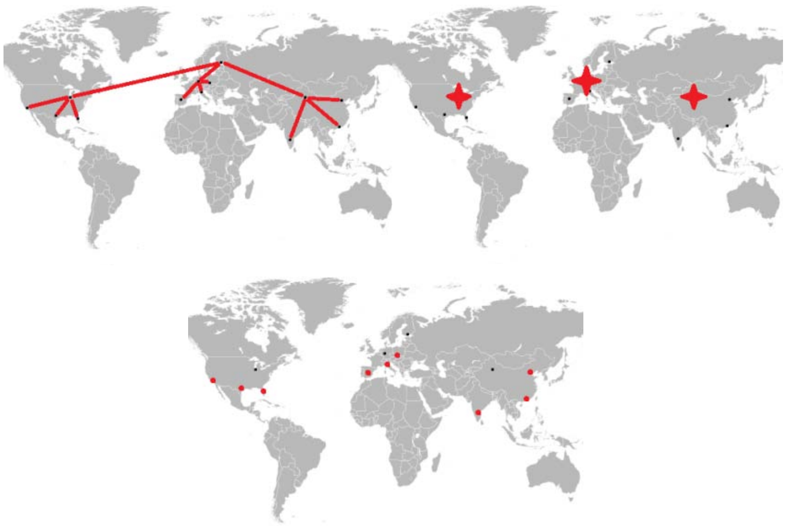

***Figure 8.5.*** *Relocating production further into the downstream – production on the way, wholesaling level personalization and retail level personalization*

In this scenario, the small size of machinery could enable the process, if there is no space for large-scale machinery e.g. on a boat or in a shop.  Therefore, the reasons to investment on miniature production equipment relates mainly to add-on sales. Customers might choose the product because it is more personalized (personalization at wholesaling or retailing level) or because the delivery is faster (production on the way). In addition, costs of logistics and capital costs are expected to decrease as products are produced on the way and the stocks of products and semi-finished products decrease. In addition, the scenario might enable some product characteristics. For example, perishable products and groceries can be produced on the way (Kawaharae et al., 1997).

Relocation the production is a possible application for microfactories. However, it is not sure whether it is always feasible or profitable. Some factors for and against are discussed in the sub-sections below.

### 8.3.1. Production on the way

Kawahara et al. (1997) introduced the idea of a mobile factory (see Figure 8.6). Because of the small machine size, the production system could be integrated e.g. into a car. The materials could be loaded into a car and the manufacturing would happen on the way. In the end, the car could deliver completed products. (Kawahara et al., 1997) Similar system could embed into a truck, train, ship or aeroplane. Shipment by sea takes usually the longest time, so it would be the most potential application in author's point of view. Suitable products would be especially small and perishable products having a long time of delivery and a stabile demand. The process could shorten delivery and enable production of perishable products on the way. Kawahara et al. (1997) state that it would be especially effective with goods whose freshness is extremely important (ibid).

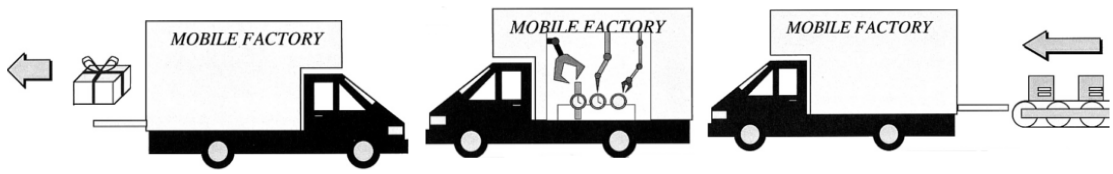


***Figure 8.6.*** *Mobile Manufacturing System – Loading materials, manufacturing on the way and delivering the products (adapted from Kawahara et al., 1997)*

However, the production on the way might not shorten much the delivery time. The production of a product is usually only a small fraction of the delivery time. The total delivery time does not decrease a lot, even if the product could be produced on the way. Therefore, the capital coasts would not decrease much either with the stocks decreases. In addition, the production equipment and handling require space e.g. on a ship. More products can be packed tightly in the ship in a normal way.

### 8.3.2. Wholesaling level personalization

The second option to relocate production further into the downstream, is to place some production steps between factories and retailers (see Figure 8.5, in the middle). Production could be placed either in storages or at wholesalers. The model would suite well for small products having modular design and an intermediate level of personalization. A company could do it in order to increase wholesale level mass customization, and increase dynamics of the supply chain and delivery. Smaller production hubs would also help to adjust to a fluctuating demand. In addition, it might enable a higher level of personalization and the customers might choose the product because it is more personalized, causing add-on sales.

The author emphasizes that a lot of uncertainty relates to the cost savings. The potential impact on costs of logistics depends highly on the processes. If part of an assembling process is personalized, the components have to be transported to many locations instead of one factory. As a result, the costs of logistics might even increase. However, coating, marking and subtractive manufacturing processes include much less logistics.

### 8.3.3. Retailing level personalization

The last option to relocate production further into the downstream, is to place part of production at retailing level, at level where the products are bought (see Figure 8.5, on the right). Kawahara et al. (1997) use term ‘fabrication in a shop’. Personal cosmetics, watches, jewellery and contact lenses are given as examples. A miniaturized chemical reaction system could be used e.g. to synthesizes the best cosmetic based on customer’s skin. (Kawahara et al., 1997) In addition, the term “point-of-need” fabrication is linked to retail level personalization in many cases.

To sup up, microfactories could be used to personalize in retailing level small and highly personalized products e.g. contact lenses, watches, jewellery, cosmetics, small sport equipment, pharmaceutics and other medical products. Miniaturized personalization processes include painting and UV-printing (e.g. laptops), marking (e.g. jewellery), final assembly (e.g. glasses), machining (e.g. custom-fit sport equipment) and sorting (e.g. drug dosage and encapsulation).

In some industries, certain processes already take place at retail level. For example, Verkkokauppa.com is a Finnish online retailer of home electronics. Tirkkonen (2011) states, that Vekkokauppa.com has personalized products since 2007. They have a laser carver, a UV-printer and a vinyl printer. Multiple products can be personalized with customer’s pictures (Tirkkonen, 2011). Similarly, Apple provides laser engraving for iPods or iPads (Apple Inc., 2011). Goldsmiths have engraved watches and jewellery already for ages. In addition, personalization is a key element of many businesses as optician and orthotics. Furthermore, low-end sport equipment and guns are usually standardized and the low-end products are custom fitted to a customer. In general, miniature production systems could enable more processes at retail level.

However, retail level personalization includes certain limitations and drawbacks. First, the same logistic dilemma relates to retail level as wholesale level. The costs of logistics might increase. If assembling process is personalized, the components have to be transported to many locations instead of one factory. Coating, marking and subtractive manufacturing processes are more potential processes instead. On the other hand, the number of personalizing retailers includes a compromise. Only few customers can be served with few retailers but a large amount of retailers increase costs. In reality, companies might choose to personalize only in large flagship stores for marketing purposes, and centralize the service for other customers. In addition, the retail level customization should relate to some products which can be bought on impulse. If a customer wants to buy a personalized product, he or she can usually wait few days.

## 8.4. Manufacturing on the spot

The last scenario, on the spot manufacturing, relates to the speculated 'ubiquitous manufacturing' (Okazaki, 2010), 'point-of-need manufacturing' and 'decentralized manufacturing'. Products could be produced by microfactories in a place they are used. It includes to two different cases, according to what substitutes the use. On the one hand, something can be produced on the spot instead of ordering. On the other hand, ordering is not the substitute in e.g. education or prototyping. With education, the process is the product. Similarly, the process provides information for prototyping.

Here, the small-size equipment enables the production and the whole business. For example, classrooms, laboratories and engineering or design offices are not designed for large machinery. The small machines fit well into the non-manufacturing environment.

### 8.4.1. Production on the spot instead of ordering

As microfactories are small, they could be used to produce products on-the-spot in various locations. It would be ideal for small products having critical time of delivery, e.g. exchange parts (Kawahara et al., 1997), spare parts (Okazaki, 2010) and medical products (Heikkilä et al., 2008). There are three principal reasons: no space for a traditional factory (e.g. urban fabrication in a city centre), no time to deliver (e.g. battlefield) or impossible logistics (e.g. researchers' special conditions). Other special locations include oceans and space. One specific application area is medical applications. Microfactories could be used for fabrication of custom implants (Heikkilä et al., 2008); dental applications (Okazaki, 2010; vhf camfacture, 2010); drug fabrication, dosage and encapsulation; as well as sterilization. Battlefield (King & Jatoi, 2005; Barkley, 2009), trouble spots and the third world are examples of situations where logistics can be problematic.

***Figure 8.7.*** *Examples of US Army point of need processes: the Mobile Parts Hospital (Barkley, 2009) and the Mobile Army Surgical Hospital (King & Jatoi, 2005)*

The US Army has two good examples of point of need processes: Mobile Parts Hospital and the Mobile Army Surgical Hospital (see Figure 8.7). According to Barkley (2009), the Mobile Parts Hospital (MPH) is a portable replacement part factory. A MPH includes machinery and three machinists. In 2009, US Army had three MPHs in Iraq, Kuwait, and in Afghanistan. Since 2003, more than 100,000 critical parts have been produced at points of need. The machinists make CAD drawings based on a broken part, drawings and verbal descriptions. When the CAD drawings are approved, a new part is fabricates in few days. Later on, the CAD drawings will be sent to other units. The point of need fabrication can provide huge cost savings. For example, the MPH made a rotor brake seal for an Apache helicopter. Instead of shipping the rotor back to the States, the helicopter could be used within days, and $393,000 was saved. (Barkley, 2009)

According to King and Jatoi (2005), the Mobile Army Surgical Hospital (MASH) is a container hospital, including surgeons and medical equipment. The concept was born already in the World War II. MASHs are used to for immediate and lifesaving surgical care in the field. (King & Jatoi, 2005) Microfactories could be used in a container, in MPHs and MASHs, for distinct processes because there is not a lot of space.

### 8.4.2. New applications for automation and production technology

The last applications are part of point of need applications and ubiquitous manufacturing (Okazaki, 2010) as well. However, contradictory to the previous sub-section, ordering a product is not a direct substitute for using a machine locally. The applications are mostly new for industrial automation and machinery.


***Figure 8.8.*** *Roland Introduces iModela iM-01 (Roland DG Co., 2011b)*

The most potential applications are prototyping (e.g. in engineering, design, or architecture office) and educational use. In addition, miniaturized automation could be used in laboratories (e.g. DYNEX Technologies, 2007a, 2007b; BPC BioSede SRL, 2009a, 2009b; Biohit, 2011a, Pfriem et al., 2011) and for processes inside of industrial and laboratory equipment (Eichhorn et al., 2008). Ordering or subcontracting is not usually a substitute because the process is the product (prototyping and education) or subcontracting is impossible (in a laboratory). Microfactories could be used even for personal fabrication, selling the equipment for consumers and communities. The iModela iM-01 (see Figure 8.8), an affordable 3D hobby mill designed by Roland DG Corporation, is a good example of home fabrication (Rolanda DG Co., 2011b).

There are interesting ideas of personal fabrication in the book “Fab: the coming revolution on your desktop - from personal computers to personal fabrication”, written by a MIT professor Neil Gershenfeld in 2007. Gerhenfeld (2007) organized FabLabs, sets of small and expensive manufacturing machines. A FabLab included a laser cutter, a sign cutter, a waterjet cutter, a milling machine, an electronics assembly station, microcontrollers for programming and a NC mill. A group of MIT workers and students brought the FabLabs around the world and let people produce things they wanted. As a result, the FabLabs were used for e.g. personalization of shoes, jewellery fabrication, building a sheep localization system and electricity meters. (Gershenfeld, 2007)

## 8.5. Observations from the interviews

In the interviews, the applications were discussed both with equipment providers and users or potential users. With the equipment providers, both industry and the applications of the customers were discussed. With the users, the exact processes and applications were discussed. In addition, potential applications were discussed with few companies which might benefit from microfactories.

To sum up the interviews, microfactories are currently used in the industry as a tool for component manufacturing and assembly processes. Flexibility requirements are too high for microfactory lines. Conveyors are against some new production paradigms, e.g. Lean. In the future, educational, laboratory and office use are promising. Local cleanrooms interest companies, especially in the bio industry. However, they require still development and standardization. Retail level personalization includes problems relating to logistics and business models. Home fabrication will be likely a relative small niche in the near future. In addition, the MEMS industry might not be the case.

According to Vesa Hirvonen (2011), MAG Lean cells are used mostly in the electronic and life science industries as well as within component manufacturers (e.g. in the automotive industry). Processes include e.g. screw insertion, precision assembly steps, plasma treatments, dispensing, marking and cleanroom processes. In addition some special processes and assembly are combined into one cell. (Hirvonen, 2011) Mika Laitinen (2011) states that, in the beginning of MAG Lean developed, the applications concentrated on electronics and the telecommunication industry. Later on, production processes of other handheld-size products embedded into the business. For example, production of wobblers was one speculated application. Ideas of portable or mobile factory (q.v. 8.2.1 and 8.3.1) also came up. (Laitinen, 2011)

Alain Codourey (2011) states, that the watchmaking industry is the largest industry for all the products of Asyril. In addition, the medical and semiconductor industry have applications (see Table 6.1). Applications include e.g. pick and place, palletizing and other standard applications. Asyril provides mostly machines for standardized processes. Specific applications (e.g. manufacturing systems and gluing cells) of the end-users are fulfilled via CP Automation and other system integrators. The customers prefer individual machines instead of lines. (Codourey, 2011)

According to David Hériban (2010), Percibio Robotics aimed for the MEMS industry in the beginning, as it was often referred within the academics. However, the companies in the industry were not highly interested of the new products. It turned out that the industry already has long-time (up to 20-year) technology roadmaps. The companies wanted to develop the old processes. The system of Percibio Robotics would have been too different. Therefore, Percibio Robotics had to rethink the market. Potential applications in the clockwork industry were found. The applications include e.g. placing small stones in the encore of the motion and placing axis for gears in as small hole with a precision of 10 µm. (Hériban, 2011)

The only interviewed company which uses desktop factories was Nokia. Andy Zott (2011) describes that the desktop cells are currently used as a tools for Lean assembly steps which cannot be conducted by humans. Human loads a cell and the cell conducts a specialized task. (Zott, 2011) According to Jari Luotonen (2011), the desktop processes include screwing, gluing and precision assembly. For example, components might have small gaps at joints. If the component is glued exactly in the middle, the gap is as wide on every side and human eye does not see the difference. However, human operator would not be able to place it precise enough. (Luotonen, 2011) Biohit wants to use desktops to support Lean production as well. Härkönen (2011) states, that the desktop factories could be used for two purposes. First, they could be used to Machining of injection moulded components on the spot, during the assembly. Second, the desktop factory units could be used for flexible co-operation between humans and machines, including e.g. small 6 DOF safety robots, minimizing the safe areas. (Härkönen, 2011) For more information about Nokia and Biohit, please refer to the section 6.3.

In addition, two interviewed companies, Suunto and Vaisala, have Lean assembly but the products are produced mainly manually. Teemu Suominen (2011) describes that Suunto has most of the assembly and injection molding in Vantaa Finland. In addition, most of the components are bought from China. However, the demand of watches fluctuates and delivery of the components takes three months. The assembly takes only one day instead. Automation is not used because the watches have difficult structures. The watches include e.g. multiple layers, flexi cables between the layers and the layers can't be only stacked together. (Suominen, 2011) The author noted that the assembly have similar elements than Nokia. It is divided into Lean cells and products are assembled with simple tools, e.g. electronics screwdrivers. Design for assembly procedures could enable use of microfactories. Microfactories could be used as stand-alone processes to enhance quality and efficiency. Vaisala had a similar situation.

In addition, challenges relating to few industries were brought up. Tomi Piertari (2011), testing and maintenance manager at Vaisala Oyj, evaluates that desktop factories could be used for sensor assembly. Currently, the sensor assembly includes cleanroom processes and final assembly. First, the sensors are produced on silicon wafers in a cleanroom including standard semiconductor processes. Secondly, the silicon wafers are cut into separate sensors. Finally, the sensors and/or measuring devices are assembled outside the cleanroom in a controlled cabinet. The silicon wafer processes might not suite well for microfactories as the wafers are large. However, the Lean assembly of measuring devices outside the cleanroom could be enhanced by microfactories. Traceability and monitoring of the assembly process are vital. In addition, cleanliness is important for the joints. Local cleanrooms could be useful. (Pietari, 2011)

The medical industry might be one potential field of applications. However, it is challenging for equipment and automation providers. Härkönen (2011) stresses, that the medical industry is highly regulated. For example, ISO 13485 certificate is required and the products require different validation and certification. In addition, it is vital to understand the industry and the application area. (Härkönen, 2011) Harri Heino (2011) believes also in on-the-spot medical applications. Instead of having all the different variations of implants on stock, a hospital could have bulk implants and specific machine to personalize them. Especially specific operations e.g. face and scull surgery, would benefit of the personalized implants if the amount of surgeries could be decreased or they would shorten dangerous operations. In case of average fracture, the surgeon has enough time to modify the implants. However, metallic implants might be the first applications. The manufacturing processes of biodegradable implants are still under development. (Heino, 2011)

Finally some applications do not appear as brilliant as expected. Pekka Tirkkonen (2011) states, that Verkkokauppa.com has personalized the products since 2007. They have a laser carver, a UV-printers and a vinyl printer. Multiple products can be personalized with customer’s pictures. Using microfactories for personalization includes two problems. First, the personalization process is completely manual. After the picture has been received, an employee brings the product from the warehouse and opens the box. The printing takes about 5min for a laptop. Finally, the products are packed manually into the boxes. It would be more difficult and costly to order bulk products from the providers. Small batches are more expensive and they do not want to change the business model. Secondly, larger equipment, instead of smaller, is needed to personalize home electronics e.g. 64” TVs. Smaller equipment could be used parallel e.g. for MP3 players and phones. However, the specific machines, e.g. UV printers, are already relative small. (Tirkkonen, 2011)

A member of Helsinki Hacklab, a communal workshop in Finland, was interviewed to find out about their 3D printing projects and home fabrication aspects. Eero Heurlin (2011) estimates that there would be some demand for inexpensive machines. For example, a composing machine, a low precision milling machine (for fabrication of circuit boards), a laser cutter and a CNC machine would be needed. However, he estimates that the first company could not make profits out of the cheap machines. The price point is really low and there are only few customers. Instead, low-end 3D printers have gained more popularity. There are already commercial machines in the market and because a critical mass might be obtained. What is positive for developers of such cheap machines, the robustness is clearly not a big issue. A community, such as Helsinki Hacklab, would fabricate e.g. 5 circuit boards in a day. However, user-friendliness is important. Simple point and click software is needed. (Heurlin, 2011)

## 8.6. Roadmap

In conclusion, microfactories could use to manufacture any small components and products which fit into the reduced working space. There are applications with versatile level automation throughout and beyond traditional supply chain. In this section, the applications are placed on a timeframe (see Figure 8.9). It combines both the literature, empirical evidence and the observations from the interviews.

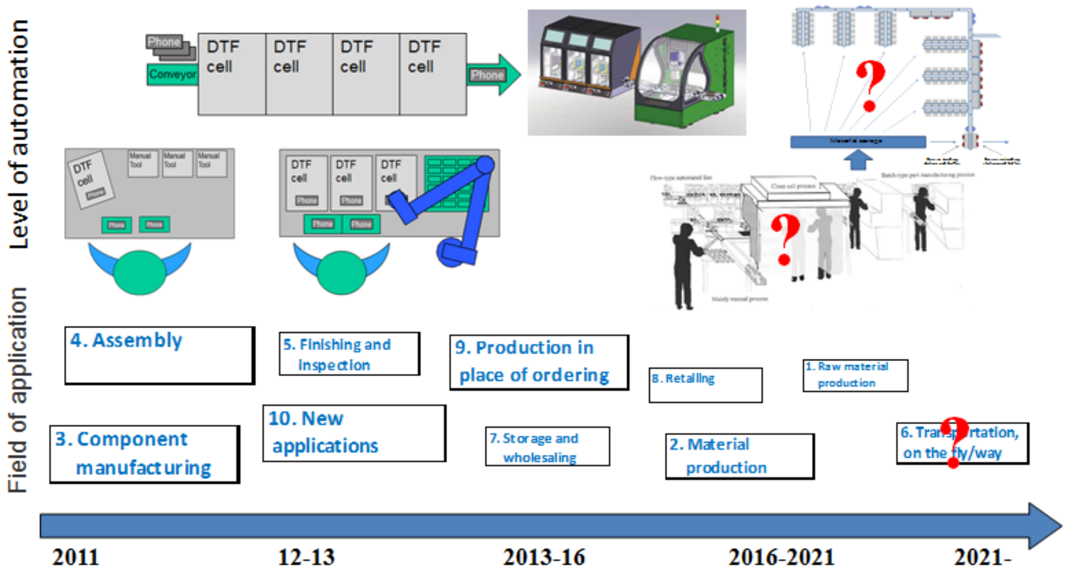


***Figure 8.9.*** *Application roadmap for microfactories*

The roadmap (see Figure 8.9) consists both the level of automation and field of applications. Currently, microfactories are currently used in the industry mostly for automated assisted manufacturing as stand-alone machines (Endo, 2010; Härkönen, 2011; Luotonen, 2011; Zott, 2011; Codourey, 2011). The equipment lacks of standardization. In addition, flexibility requirements are too high for microfactory lines in many cases (Luotonen, 2011; Zott, 2011; Codourey, 2011). Few line-based systems are on the market (Hofmann et al., 2011; JOT Automation, 2011). However, one key element is adaption to different levels of automation: manual, semiautomatic and fully automatic production.

In author's point of view the next step is combining microfactories to low level automation (Zott, 2011) and small stand-alone production lines. Here processes are divided into individual cells, but the system is designed for automated assisted manufacturing. If it benefits for both companies, few companies can agree on standards and such lines can be built out of multi-vendor machines. However, it probably takes still years that multi-vendor desktop factory systems exist. Adaption of factory systems with intelligent logistics (Järvenpää et al., 2010) takes time as well. One should note that it may not interest all the companies. Industries with stabile product technology and long life cycles, e.g. the watchmaking industry, might be the first to adapt such systems.

Currently microfactories are used mainly for component manufacturing and assembly processes. An increasing application area will probably be non-manufacturing applications such as prototyping (e.g. in engineering, design, or architecture office) and educational use. They are potential applications because there are no direct substitutes. Different finishing and inspection processes will be probably miniaturized as well. However, the small machines have be able compete with the traditional machines. Same applies to the production on the spot instead of ordering. Providers have to think how do the user use the machines and what substitutes the use. The author finds the other applications are less probable. Especially, production on the way is unlike to occur yet.

# 9. BUSINESS MODELS

This chapter focuses on the business aspect. More precisely, the business models for equipment providers are discussed. By definition, micro and desktop production systems are small and portable. In addition, they represent a new technology on the market (q.v. section 3.3). The main question relates: how do these factors benefit the equipment providers? In conclusion, the technological change provides few positive aspects and potential market segments.

The first section summarizes the observations from the interviews. In the section 9.2, the business models for small-size machining units are discussed. Similarly, in the section 9.3, business models for small-size automation cells are discussed. The section 9.4 discusses the characteristics of non-manufacturing users as a customer segment. The section 9.5 discusses the technology for subcontractors. Finally, in the section 9.6, micro and macro environment of the industry are analysed.

## 9.1. Observations from the interviews

Kalle Härkönen (2011) states, that the small size of the equipment might enable new business models. For example, Wegera is a subcontractor and a machine tooling shop. Therefore, they understand well the subcontracting business. With Kolibri, they could place the subcontracting into the customer’s business premises, with or without an employee, and make the profits out of net billing. The model works in other industries as well. For example, Fibox is a company selling modular plastic enclosures. It is a service concept, the bulk enclosures are perforated based on customer is needed. However, they could offer a small perforator machine as a tie-in deal and provide only the bulk enclosures. Charging could base on e.g. amount of finished enclosures. Similar model is used with wall paints. Retailers do not have to buy all tones of the paint. Instead, basic paints, the recipes and a paint mixer are offered as package deal. Because of the small size, the machines can be installed more easily to the customer’s premises. (Härkönen, 2011)

Härkönen (2011) adds that microfactories have already advantage as they are different than the traditional solutions. The manufacturing industry is changing from mass production to flexible production (e.g. Lean, Agile and customer orientated), supporting microfactories. However, it takes a long time. At the moment, new business models can be used as a way to enter the market. The small machines have to be able to compete with the traditional machines in some aspect, e.g. precision. All specifications do not have to be as good as in the traditional machines. In addition, many Finnish company can’t even account payback times for investments. Huge investments are made blindfolded. Equipment providers could show the customers that the investments are profitable, e.g. by offering different tie-up reports and solutions. (Härkönen, 2011)

Seppo Kauppi (2011), the project manager of Wegera Kolibri, states that Kolibri is also used for instant capacity sales. It means that the machine lies at Wegera’s premises and customer can order instant machining services for monthly payment. Because Kolibri is small, there is enough space for the machine reserve. However, the service has not been bought yet. In addition, the small size enables new customer segments. For Wegera, one significant market segment might be prototyping and educational use. One CNC machine is already sold to a school. The fact, that Wegera is both a machine tooling shop and the provider of Kolibri, helps the business as well. Own subcontracting can provide parts and test the machines. Furthermore, the machine development markets the subcontracting services. (Kauppi, 2011)

In addition, microfactory providers can provide the equipment to end-users and system integrators or both, as Asyril. Codourey (2011) describes that, together with CPA, Asyril’s products can be sold both for end users and system integrators. Asyril cells the standardized desktop cells for the end customers, as well as robots and feeding devices for system integrators. In fact, Asyril is selling more desktop cells as there are not many system integrators as customers. In addition, CPA integrates Asyril’s products for special applications, e.g. manufacturing systems or gluing cells. (Codourey, 2011)

Instead, Master Automation Group is based on more traditional business models. Vesa Hirvonen (2011) states, that the sales are based mainly on direct sales. In addition, maintenance service, technical support and spare parts are provided. In some cases, leasing is also provided but MAG prefers direct sales. Financial companies can provide the leasing if needed. Regular support can be offered as well. One important customer in the telecom industry has employees of MAG in the production. (Hirvonen, 2011)

Mika Laitinen (2011) states, that small and low-cost automation includes risks as well. Traditionally, automation providers sell machines and maintenance services. Maintenance services can cover up to half of annual revenues. In addition, the service business is important because the cash flow is more or less constant, enabling cash flow financing. Direct sells provide irregular profits. It is a risk that the small and low-cost automation becomes disposable automation. If the machines are not maintained, cash flow financing disappears. As a result, other business models, e.g. leasing and capacity sales are needed. In addition, the lack of small-size components and subsystems is a problem. In-house development includes risks. On the one hand, small amount of order does not generate enough profits. On the other hand, large amount of orders includes a risk. If one component breaks down all the machines have to be fixed. (Laitinen, 2011)

## 9.2. Small-size machining units

As Kalle Härkönen (2011) stated, the small-size of the machining units might enable new charging/business models, e.g. leasing, tie-up sales and capacity sales. Small machines can be carried in e.g. with a pallet jack, and the space at customer's premises, does not require any preparations. (Härkönen, 2011) The business model can be anything between direct sales, leasing and package deals. Leasing can be sold with different names as well. For example, high-end digital backs for studio cameras are sold with "capital insurances". In other words, the first digital back costs the full price. If the customer updates the digital back within given time period, the provider recompenses a certain percentage of the original selling price. For example, 70% of the price will be recompensed if the customer updates the digital back within two years. The same model could be applied for production machinery as well. As the miniature production systems are new, ccustomers are more likely to accept the new charging models.

Wegera, or any other company providing small-size machining units, could provide free or inexpensive machines for the customers and charge the use. It is kind of leasing but it enables Wegera to move the machine elsewhere if needed. Charging is only a matter of a contract, e.g. €/hours, €/working hours or €/produce. Depending on a customer and the contract, an employee could be provided as well. The model decreases the buying decision. As discussed in the chapter 4, investments include always risk and large investments might be frightening for companies. In addition, many small and medium size companies do not evaluate the investments broadly enough. It is therefore easier to justify cash flow financing. Furthermore, buyer's shifting costs increase. The machine at customer's premises binds the customer. It becomes more difficult to change provider.

On the other hand, the small size enables capacity sales, i.e. the machines lay at provider's premises and only capacity is sold. As the machines are small, more machines can be placed at provider's premises. Seppo Kauppi (2011) describes that Wegera is providing already such service. Customer can order instant machining services for monthly payment. (Kauppi, 2011) In addition, the provider could have multiple machines on stock and provide a service of capacity scaling. In this case, the provider would adjust the amount of machines, either in customer's or provider's premises, based on how much capacity the customer needs. Okazaki (2010b) also refers to similar business model "delivery service of machine tools". However, both the business models, tie up sales and capacity sales, increases capital requirements, and thus marginal utilities (q.v. 4.1.2) have to be counted.

## 9.3. Small-size automation cells

For equipment providers, the technology offers two promising customer segments: Lean manufacturers and manufacturers with fully loaded factories. First, Lean manufacturers are a promising segment because Lean is contradictory to traditional automation (Zott, 2011; Codourey, 2011; Hériban, 2011). Lean is much more than the production methods (q.v. 3.2.3). However, it appears that Western companies tend to adapt primary only the Lean tools and method invented by Toyota (Hines et al., 2004). For the equipment providers or system integrators, the impact of those principles is the only thing that matters. For example, many ‘Lean’ manufacturers favours nowadays pull production (with *Kanban*), one-piece-flow and automated quality control methods.

As a result, production is divided into Lean cells (islands of excellence) and the production is mainly manual. Therefore, automated desktop cells suite well for the production. They can improve quality and enhance efficiency within the Lean production cells. In the beginning, the author believed that the term ‘Lean’ (e.g. ‘Lean Desktop Factory, ‘MAG Lean’ and ‘JOT Lean’) is just a way market the equipment. However, it appears that the compatibility to Lean production might be actually the largest benefit of the systems. The CEO of JOT Automation, Mikko Sipilä, cites the “next coming of lean assembly” as one of the major trend for automaton as well (Sipilä, 2011). The JOT Lean production system is built for Lean and scalability of automation.

However, Lean and Agile manufacturers are a potential customer segment but it is not easy for the automation providers. As discussed in the sub-section 3.2.4, Lean production has relative different requirements and evaluation criteria for production machines (see 3.2.4 and Table 3.2). For example, the reliability is important for traditional mass production as the production volumes are usually huge. However, there are safety stocks in case of breakdown. On contrary, Lean tends to favour robust and thoroughly tested technologies by offset. In case of a breakdown, there are no (or small) safety stocks. In addition, *Jidoka* and *andon* stop the process for sure.

The manufacturers with fully loaded factories relate to the fact that the floor space is relative cheap (€/$m^2$), even with all the fixed costs. However, acquiring new space includes huge step costs. It offers a major competitive advantage for a provider of miniaturized production system. For example, there might be two solutions for a given production process on the market (q.v. section 4.4). Even if the smaller option is more expensive, it might be selected because it fits well into the factory layout.

## 9.4. Small-size equipment for non-manufacturing use

In the non-manufacturing market segment (q.v. 8.3.2), the small size of machinery can be a major competitive advantage as well. The non-manufacturing environments, e.g. educating in classrooms (e.g. Techsoft UK, 2010a, 2010b; Rolanda DG, 2011a, 2011b); prototyping in engineering, design and architecture offices (e.g. 2BOT physical Modeling Technologies, 2010; Dimension, 2010; Objet, 2010a, 2010b, 2011); and automating laboratory and analysis processes in laboratories (e.g. DYNEX Technologies, 2007a, 2007b; BPC BioSede SRL, 2009a, 2009b; Biohit, 2011a, Pfriem et al., 2011), are not build for heavy and large-scale machinery. In addition, there are no direct substitutes for the use. If, for example, an engineering company wants to buy a CNC machine for prototyping in a small office, the large and heavy machines are not reasonable options. Seppo Kauppi (2011) evaluates that the non-manufacturing customer segment will be an important market for Kolibri. (Kauppi, 2011)

However, retail level product customization has a different setting. For a retailer, it is important to own the machine only if the products which can be bought on impulse. If a customer wants to buy a highly personalized product, he or she can usually wait few days to get the product from a factory. Therefore, the retailer can substitute the production by ordering the product from a factory.

Similarly, personal fabrication includes a different setting. If a customer is using the machine only because of pure pleasure, the process is more important than the product. Therefore, it is not substituted easily. However, if a consumer produced utility articles for itself, there is always an option to buy the component elsewhere. According to the authors's observations in the Helsinki Hacklab, designing of the complete system is the main thing for the hobbyists. Components can be bought elsewhere. In addition, it appears that home fabrication will be still a small niche for many years to come. The desktop-size hobby 3D printers have gained more popularity. Users are designing new objects to print and sharing them online (Thingiwerse, 2011). Therefore, the industry has strong network effect and the critical mass might be already obtained. It is possible that desktop-size machining units will gain more popularity in the future as well.

## 9.5. Subcontracting with small-size machines

Finally the small size and modularity of microfactories might enable some new business models for subcontractors. For example, a subcontractor or a contract manufacturer can acquire a stock of multiple small-size process modules. Based on orders, different production lines can be built out of the modules and more customers can be served. Because of the small size, more modules fit into the space. The subcontractor can be the equipment provider but they can be separate companies as well. Apparently, the Japanese manufacturers have used microfactories for this purpose (see Endo, 2010). Seppo Kauppi (2011) sates, that subcontracting is excellent counterbalance for machine development. Subcontracting can provide parts for the machines, and the machines can be tested in own production. (Kauppi, 2011)

In addition, the small of machinery can enable a portable maintenance service. As described in the sub-section 8.3.1, US Army has Mobile Parts Hospitals (MPHs) for replacement part fabrication (Barkley, 2009). A similar model could be expanded into other industries as well. A company could provide spare parts for factories and other machines. Okazaki (2010) states that the spare part production is a potential application.

## 9.6. Analysis of micro and macro environments

In this section, the micro and macro environment of micro and desktop production systems are roughly scanned by Porter's five forces analyse (q.v. 3.4.1) and PESTEL analyse (q.v. 3.4.2). The industry includes companies providing microfactories as well as different desktop-size stand-alone production units. The both compete with traditional solutions. In many cases, the miniaturized production systems would replace the traditional large-scale machines. The analysis focuses partly on this competition.

### 9.6.1. Porter five forces analysis

This sub-section analyses the competitive forces of the industry of micro and desktop production systems, in equipment providers' view. (see Table 9.1).

***Table 9.1.*** *The industry of miniature production systems – Porter's five forces analysis*

| | Positive | Negative |
|---|---|---|
| **Rivalry** | • Industry structure<br>o Low amount of companies<br>o No clear market leader<br>o Relative fast industry growth<br>• Easy capacity expansion<br>• No exit Barriers<br>• Low network externalities | • Mobility of the product (combined with the global competition)<br>• Moderate economies of scale (±)<br>• Global competition (±) |
| **Entry** | • Readiness to defence<br>• Scarce recourses (e.g. reputation)<br>• Customer loyalty to established brands<br>• Economics of scope<br>• Low profitability (in the beginning) | • Small capital requirements<br>• Economies of product differences<br>• Difficult access to distribution<br>• Low amount of patents<br>• Low amount of regulation<br>• Low customer switching costs (±) |
| **Substitutes** | • The amount of perfect substitutes (±) | • The amount of functional substitutes<br>• Products competing the same purchasing power |
| **Suppliers** | • Moderate Supplier concentration (±)<br>• Low supplier switching costs (±)<br>• Suppliers can't integrate forward vertically (±) | • Small amount of suppliers<br>• Need of differentialized products<br>• Suppliers' products have large impact on the product quality<br>• Suppliers' low learning curve<br>• The industry is an important client |
| **Buyers** | • The product is not standardized<br>• Large amount of buyers<br>• Buyers are not concentrated<br>• Low price sensitivity<br>• The product is differentialized | • Low buyer switching costs<br>• The ability to integration backward (±)<br>o Asia vs. Europe |

In conclusion, the suppliers and substitutes are the most notable treats. Substitutes have a critical role because only few miniaturized components and subsystems exist. In addition suppliers' products have large impact on the quality of the miniature production systems. Substitutes are treats because the miniature production system can be easily replaced with traditional production equipment. Entries form a moderate treat because there are only few barriers to entry. However, rivalry within the industry and buyer's bargain force are not yet large treats.

Rivalry within the industry is relative peaceful. Few factors increase the rivalry, e.g. mobility of the product and economies of scale. Microfactories are small and portable (mobile) by definition. Compared to traditional large-scale production equipment, they can be shipped fast and easily e.g. by aeroplane all over the world. It increases the global competition. In addition, the products have moderate economies of scale. However, the development period of a new production technology can be as long as years. The R&D costs are unit costs.

The factors restraining the rivalry within the industry include e.g. industry structure, easy capacity expansion, a lack of exit barriers, low network externalities and global competition. The industry does not have a large amount of companies yet. The companies are relative similar and there isn't a clear marker leader. In addition, the industry has moderate growth, and all the systems on the market differ from each other. Therefore, the companies can focus on different market segments and they do not have to compete repeatedly on the same customers. Similarity would cause more intense price war. In many industries, capacity can be aumented only through large increments. Furthermore, the overcapacity may lead to price war. However, this is not the case in the industry of miniature production systems. There are no extensive exit barriers (e.g. legal or cognitive) in the industry. Low externalities refer to the lack of dominant design, standardization and complementary goods. Dominant design attracts more system and equipment providers. Complementary goods are e.g. other compatible cells, standardized machines and tools. In addition, the globalization is also a positive element. Equipment providers do not have to fight on the customer in a specific area.

New entries form a moderate force because there are only few barriers to entry. The industry has e.g. relative small capital requirements and low customer switching costs. In the beginning, miniaturization of production equipment includes R&D efforts (for traditional automation providers). Apart from that, the industry doesn't have large capital requirements. In addition, all the systems on the market differ from each other. Thus, the entry doesn't have to fight against dominant design. Furthermore, the distribution channel is rather open for new entries, and there is no notable regulation or patents preventing the entry. For a regular customer, it's rather easy to change the production equipment. The customers' products (for ex. in medical and electronics industry) have short life cycles. Therefore, they can change the production technology between the product generations. However, new entries have to gain the reputation.

However, few factors create barriers of entry, which is positive for the companies already in the industry. Some of the Asian and Japanese companies have been on the market already for ten years or more (desktop-size machining units). They might defence the market causing a minor barrier to entry. In addition, the customers of production equipment prefer reliability and they are loyal for the established brands. Thus, intangible recourses (reputation) are highly valuable. It forms a moderate barrier to entry. In addition, companies have some strategic advantage on the old R&D development as well as on the similar scalable production lines. Even though production machines and equipment have high profits, the R&D causes high fixed costs.

Substitutes are one of the most notable treats. Substitutes include all the products having negative impact on the demand of a given product. Substitutes can be divided into perfect substitutes, functional substitutes and products competing over the same purchasing power. Perfect substitutes include e.g. other automation units, production machines and machining units. However, in a ship, a classroom or a laboratory, there is shortage of space. Desktop-size machines might be required. Functional substitutes are all the traditional production machines with different level of automation. There is a reliable traditional machine or solution for almost all the applications. In addition, investments on miniature production systems compete with customers' every investment to improve profitability.

Supplier's bargaining power is also a notable treat. Only positive factor is the low concentration of suppliers, i.e. multiple component and subsystem providers exist (in general). However, the group of companies providing components and subsystems is more concentrated than the group of companies developing miniature production systems. Supplier switching cost is relative low, i.e. some components of a machine can be changed easily. Only the functionality matters for the end customer. However, the quality of components defines the quality of the equipment. Customers tend to evaluate the systems also based on the components. In addition, for the subsystem providers, there are no barriers to enter the market. However, it requires relative high R&D efforts.

On the other hand, multiple factors increase the supplier's bargaining power. The lack of miniaturized components and subsystems (e.g. axis, manipulators and end-effectors) is one of the main problems with the technology development. The miniature production systems are unique and they need unique miniature component suppliers. In addition, the quality of components defines the quality of the products. In-house development requires a lot of resources, and thus the small group of providers and suppliers has relative high bargaining power. Furthermore, the industry of miniature production system is remains relative narrow. It is not vital for the suppliers. For example, small axis and camera systems are used for multiple other applications as well.

Instead, buyer's bargain force is not a significant treat for the industry. The only negative factor is the low buyer's switching costs. As noted above, for a regular customer, it's rather easy to change the production equipment. It is the case especially if the customers' products have relative short life cycles. Therefore, the production equipment can be changed between the product generations. For the customers, the ability to integrate backwards, i.e. develop own machines out of suppliers' components, is relative low as well. Companies want to concentrate on their core business. However, e.g. in Asia and Japan, some of the biggest electronic manufacturers do develop their own manufacturing systems. However, it is relative rare in Europe. One additional risk relates to the buyers. If an equipment provider is focusing on a too narrow market segment, the customers become more concentrated than the providers. Therefore, the customers might be able to dictate the product development and cut some of the profits.

However, multiple factors decrease the buyer's bargaining power. The product is not standardized. Usually every provider offers something individual, and there are many customers with low concentration (see an exception in the end of previous paragraph). In addition the customers are not price sensitive. As in business to business markets in general, the customers prefer performance and reliability over the price.

### 9.6.2. PESTEL analysis of the macro-environment

Major trends, affecting to the business in the 21th century, were discussed in the section 3.1. According to the PESTEL analysis, current trends in the macro environment tend to favour micro and desktop production systems (see Table 9.2).

***Table 9.2.*** *The industry of miniature production systems – PESTEL analysis*

| | **Positive** | **Negative** |
|---|---|---|
| **Political** | • Growth of Western manufacturing?<br>• Engineer education | |
| **Economic** | | • Economics in USA and Europa |
| **Social** | • Growth of Asia<br>• Demographic change<br>o Aging society (automation)<br>o Urbanization | • Growth of Asia<br>o Low-cost countries transfers elsewhere |
| **Technological** | • Miniaturization (e.g. Moore's law)<br>o Things tend to get smaller<br>▪ Small products to be produced with DTFs<br>▪ Possibly automation components as well | • Lack of miniaturized subsystems slows the technology development<br>o Possibly in the future |
| **Environmental** | • Growth of environmental issues<br>o Sustainable development<br>• Saving cooling energy | |
| **Legal** | • Energy saving, recycling and safety at work (laws & standards) | • Cleanroom standards (do not support local cleanrooms) |

In conclusion, some negative factors relate to economic, social, technological and legal dimensions. All the dimensions, except economic, include multiple positive factors. All in all, the macroenvironment seems to favour micro and desktop production systems.

At the moment, the economic situation in the USA and Europa is far from stable. As a worst case scenario, a new regression might follow, freezing the investments. Growth of Asia is has also impact to the industry. Fewer products will be produced in Western countries and, respectively, less manufacturing equipment will be needed in the Western countries. However, the low cost manufacturing does not disappear. Equipment purchases will be compared against Asian manual production in the future as well. Technological dimension includes one negative aspect. The lack of miniaturized subsystems slows the technology development. Finally, some legal aspects can be restrictions restriction because cleanroom standards do not support local cleanrooms.

On the other hand, politics include some positive factors for the industry. The Asia is growing fast but, at least, the politicians have noticed the situation, and more effort is placed to keep some of the manufacturing in Western countries. In addition, engineer education is high-valuated in Western countries. Micro and desktop production systems are supposed to have users also in the future. The growth of Asia can be also positive for the industry. For example, China includes a huge market for automation. The demographic change favours the industry as well. As the society is ageing, there will be fewer employees in the Western countries. Therefore, automation becomes more needed and acceptable. In addition, more people moves into cities, space becomes more expensive and space saving production solution becomes more valuable.

Technology development favors the industry because the trend of miniaturization. In author’s point of view, the miniaturization is overstated within the discipline. The fact that computers and printers got smaller, does not mean that production equipment should miniaturize as well. However, because more miniaturized products exist (e.g. portable and handheld electronics) they could be produced with smaller equipment as well. In addition, potential miniaturization of the automation components helps the technology development. Environmental aspects favor the industry as well. More emphasis is placed e.g. to energy saving and recycling (what microfactories are supposed to do). Environmental legislation has been tightened as well.

# 10. CONCLUSION

In this thesis, applications and business models, as well as commercialization, challenges and advantages relating to micro and desktop production systems were analysed. According to the interviews, research and the industry appear to have slightly different viewpoints to the miniature production systems. Within the academics, miniaturization is a general philosophy to match the products in size.

The industry understands the philosophy, but they tend to ask what the real benefits are. The small size is usually only a secondary sales argument. There is no urgency to replace the large-scale machinery. In general, a customer buys a specific process, impact or working phase. The most important factor is whether or not the machine does what it is supposed to do. Other arguments are important if there are similar machines on the market. However, one benefit for companies is that desktop systems can be used as tools. One employee can even operate multiple small-size machines. In addition, the energy saving will be probably a lot more important aspect in the future.

Based on the interviews, disadvantages include subsystem availability and price (e.g. cameras, grippers and control systems), difficult system integration (e.g. wiring, mounting and sensor integration), restrictions of micro environment (sticky effect) and other physical restrictions of small equipment size (e.g. sensitivity to vibration and power and/or force limitations). In conclusion of the challenges, price tends to decrease only to a certain point, further it increases. Precision and mass-performance ratio might not scale down as expected. In addition, force and power limitations might exclude some applications. A really small system requires other arguments than price.

In the literature, there are a broad range of speculated applications for micro and desktop production systems, relating to different advantages. The MEMS industry is usually stated as a potential industry. In many cases, the research aims for integrated desktop production systems and high level of automation including e.g. intelligent conveyors. The applications were categorized into three scenarios, relating to different benefits and what substitutes the use. The first scenario is to replace the traditional large-scale machinery by miniature production systems. The expected benefits relate mainly to different costs. However, because of the small size, the desktop solution might suite better for Lean and manual production in general. The second scenario relates to relocating production further into the downstream, e.g. production on the way or personalization at wholesaling and/or retailing level. The benefits relate mainly to add-on sales. The third scenario is to produce products on the spot by small machines. Here, the small equipment might enable the production and the whole business.

The current use of microfactories relates to the first scenario. According to the interviews, they are used in the industry mainly as stand-alone tools for component manufacturing and assembly processes. Flexibility requirements might be too high for automated microfactory lines. In addition, conveyors are against some new production paradigms, e.g. Lean. Industries include e.g. watchmaking, telecom, medical and semiconductors. Processes for desktop automation include e.g. precise pick and place, screwing, dispensing, palletizing and marking, as well as laser and plasma treatment. The miniature machining systems suite for versatile materials and applications, for example metal (e.g. micro mechanics, jewellery and watches), glass (e.g. micro-optics), plastic (e.g. hearing aids), ceramics (dental applications) and biodegradables (implants).

In the future, non-manufacturing applications, e.g. educational and laboratory use as well as prototyping are promising. Retail level personalization includes problems relating to logistics and business models. Home fabrication will be likely a small niche in the near future. Within manufacturing industry, local cleanrooms interest companies, especially in the bio industry. However, practical issues, relating to maintenance, raise questions. Basically, any small products could be assembled in microfactories. The restrictions are the working space and process requirements, relating to e.g. force and power limitations. However, the MEMS industry might not be the first industry having specific processes. Instead, the watchmaking industry is one potential industry. Swiss clockwork industry is currently under revolution. The monopolistic production of the movements will stop in 2012. More companies need to set up their own production.

For equipment providers, the technology offers two promising customer segments (Lean manufacturers and manufacturers with fully loaded factories), few additional segments and it eases some alternative charging models. Lean manufacturers are a promising segment because Lean is contradictory to traditional automation. Currently, based on Lean production principles, the production is mainly manual. Automated desktop cells can improve quality and enhance efficiency. The fully loaded factories relate to the fact that the floor space is relative cheap, even with all the fixed costs. However, acquiring new space includes huge step costs. The additional customer segments can be reached because the small machines fit well into non-manufacturing environments, e.g. offices (prototyping), classrooms (education) and laboratories (e.g. automatic pipetting).

The alternative charging models are enabled because the small machines can be carried easily in, the equipment does not require a lot of space, and facilities do not require any preparations. A company can deliver cheap or free equipment, and make the profits out of net billing, e.g. €/hours or €/product, easing buying decision and increasing buyer’s shifting costs. On the other hand, provider can to store multiple small-size machines and sell only the capacity. Similarly, subcontractors focusing on small batches can acquire multiple small-size modules on the stock and build versatile production lines can out of the modules. However, because of the machinery stock, capital requirements will increase and marginal utilities have to be accounted.

# 11. DISCUSSION

Industrial products already arise from the microfactory research. However, introduction or breakthrough of new production technologies takes time. It appears that microfactories are still in the beginning of the S-curve of technology development, and the development is systematic (i.e. sum of component and subsystem development). On demand side, production technology has relative slow technology diffusion.

So far, microfactories have reached the interest of only a certain group of academics and companies. According to the interviews, the main preventing factors are a lack of small subsystems, a lack of examples and the conservative attitudes of production engineers. Small subsystems include e.g. cameras, grippers, control systems. The lack of examples includes a vicious cycle. Companies and engineers prefer not to use new production technologies as there are few examples. Consequently, few examples arise. For companies, costs, quality and robustness are some of the biggest concerns of equipment.

To bring microfactories faster into the industry, more cooperation is needed between academics and the industry. More precisely, academics should continue on searching the limit of downscaling. In addition, they should inform the industry and the new engineers about the technology. A large scale production demonstration is needed, so that the industry would understand the potential. The equipment providers are already modifying and commercializing the concepts. In addition, the users of automation should inform the academics which miniaturized applications and processes are needed. Smaller machines consume less energy and it will benefit the general public as well.

At the moment, the optimal size for small commercial equipment might be a bit larger than the academic microfactory size. However, the optimal size decreases as the components scale down and fall in price. Currently, the academic microfactory concepts provide a platform for the research, which spawns indirect commercialization and boosts the miniature component development (see four cases in the section 6.1).

In addition, two research recommendations are given. First, more attention should be directed towards industrial and business aspects in general. As noted, the academics and the industry have slightly different viewpoint to the miniaturization. It should be explored, what the feasible applications in various industries are and what the real benefits for companies are. Cases and demonstrations should be selected respectively. Secondly, combination of Lean and miniature production systems requires more examination. It should be identified how, in practice, companies tend to combine Lean production practices and desktop automation and/or production machines.

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# APPENDICES (6 pieces)

# APPENDIX 1: MICROFACTORY APPLICATIONS

| I. Traditional supply chain | | | | |
|---|---|---|---|---|
| A. Processing Industry | | B. Piece Goods Industry | | |
| Primary reasons to invest on miniature produciton systems<br>+ Increasing profitability: cost savings<br>* Costs of facilities<br>- Rents or capital costs, heating, air conditioning, illumination etc.<br>* Clean room investement and maintenance costs<br>* Costs of flexibility, quality or manual assembly<br>* Costs of energy<br>* Costs of material<br>* Costs of waste and recycling<br>* Capital costs (set up time, cycle times etc.)<br>+ Enabling products carasteristics (fragile products) | | | | |
| 1. Raw material production | 2. Material production | 3. Component manufacturing | 4. Assembly | 5. Finishing and inspection |
|  |  |  |  |  |
| * What?<br>- Testing and analyses on the spot<br>- Oil-field investigation<br>* Why?<br>- Portable test equipment | * What?<br>- Medical<br>- Chemistry<br>- Low-volume processs industry products<br>* Processes<br>- Chemical reactions of dangerous materials<br>- Micro cultivator<br>- Drug fabrication and encapsulation | * What?<br>- Metal<br>* E.g. jevellery and watches<br>- Glass<br>* E.g. micro-optics<br>- Plastic<br>* E.g. hearing aids<br>- Ceramics<br>* E.g. dental<br>- Biodegradables<br>* E.g. implants<br>- Silicon<br>* Semiconductors<br>* Processes<br>- Injection moulding<br>- Machining<br>- Additional manufacturing<br>* 3D printing<br>* Lithography<br>* How?<br>- Fabrication in a cleanroom or under special condition<br>- Combining to 3D pringing | * What?<br>- Portable devices<br>- Precision mechanics, e.g.<br>* Watches<br>* Micro-motors<br>* Gears<br>- Micro-optics<br>- Jevellery<br>- Life science<br>- Medical/dental<br>- Semiconductors<br>- Sensors<br>- MEMS products<br>* Processes<br>- Pick and place<br>- Screwing<br>- Dispensing<br>- Laser processes<br>- Ultrasonic welding<br>- Heat tratment<br>- Pelletizing<br>* How?<br>- AAM (Difficult manual operations)<br>- Paraller/ 3D production layout<br>- Clean room assembly | * What?<br>- Small products or components, e.g.<br>* CE marking<br>* Optical control of assembly<br>* Sterillization of medical implants<br>* Processes<br>- Marking<br>* Scratching/ laser<br>- Coating<br>* Paint/ UV-printing<br>- Washing<br>- Cleaning<br>- Sterilization<br>- Optical control<br>- Packing<br>- Processes under special condition |

***Figure 1.*** *Microfactory applications within traditional supply chain – replacing the large-scale machinery with miniaturized machines and equipment*

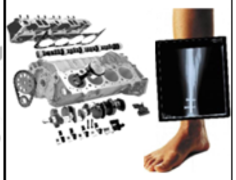
| II. Relocating production further into the downstream | | | III. On the spot manufacturing | |
|---|---|---|---|---|
| Primary reasons to invest on miniature produciton systems<br>+ Increasing profitability: cost savings and add-on sales<br>* Capital costs (stock of products and semi-finished products)<br>* Add-on sales<br>- Product customization<br>- Fast delivery<br>+ Enabling product carasteristics (perishable products and groceries) | | | Primary reasons to invest on miniature produciton systems<br>+ Enabling production and the whole business | |
| 6. Transportation, on the fly/way | 7. Storage and wholesaling | 8. Retailing | 9. Production in place of ordering | 10. New applications |
|  |  |  |  |  |
| * **What?**<br>- Small products having long time of delivery and stabile demand<br>- Pershable products<br>* E.g. grocery<br>* **Why?**<br>- To shorten delivery<br>- To protect the pershable products | * **What?**<br>- Small products having modular design and intermediate level of personalization<br>* **Why?**<br>- Dynamic supply chain and delivery<br>- Wholesale level mass customization | * **What?**<br>- Small highly personalized products, e.g.<br>* Contact lenses<br>* Watches<br>* Jevellery<br>* Cosmetics<br>* Small sport equipment<br>* Craft shops<br>* Medical<br>* **How to presonalize?**<br>- Coating<br>*Paint/ UV-printing<br>* E.g. laptops<br>- Marking<br>* Scratching/ laser<br>* E.g. iPods<br>- Final assembly<br>* E.g. glasses<br>- Final design<br>* E.g. custsom-fit sport equipment<br>- Drug dosage and encapsulation | * **What?**<br>- Exchange parts<br>- Spare parts<br>- Medical products<br>- Small products having critical time of delivery<br>* **Why?**<br>- No space for factory<br>- No time to deliver<br>- Impossible logistics<br>* **Where?**<br>- Urban factory<br>- Remoteness<br>* Space<br>* Oceans and air<br>* Researchers' special conditions<br>* Battlefield<br>* The third world<br>* **Medical products**<br>- Custom implants<br>- Battlefield<br>- Dental<br>- Third world<br>* Drug fabrication<br>* Dosage and encapsulation<br>* Sterilization | * **What?**<br>- New applications for automation and industrial machinery<br>* **Why?**<br>- The process is the product (education)<br>- Impossible subcontracting (laboratory)<br>* **Where?**<br>- Prototyping<br>* In a office (design, engineering or architecture)<br>- Education<br>* At school<br>* At Fablabs<br>- Laboratory automation<br>- Processes inside of idustrial and laboratory equipment<br>- Craft shops<br>- At home<br>* Consumers<br>* Communities |

***Figure 2.*** *Microfactory applications beyond traditional supply chain – production further in the downstream and on the spot production*

# APPENDIX 2: LEVELS OF AUTOMATION

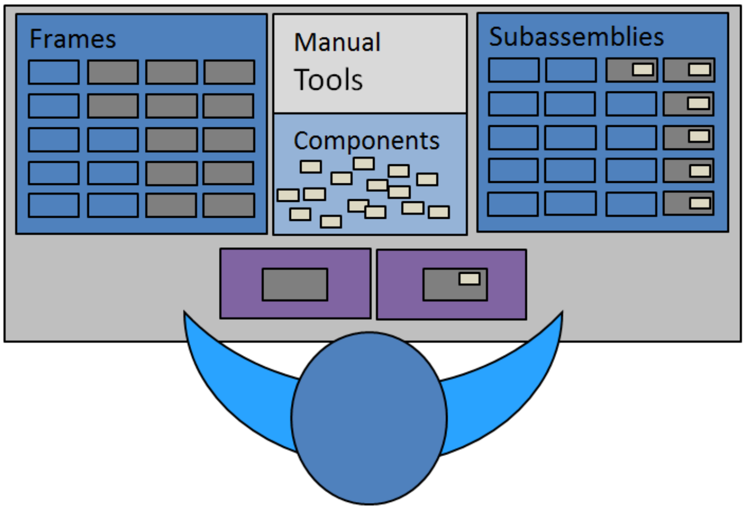



***Figure 1.*** *Manual production (see JOT Automation, 2010)*

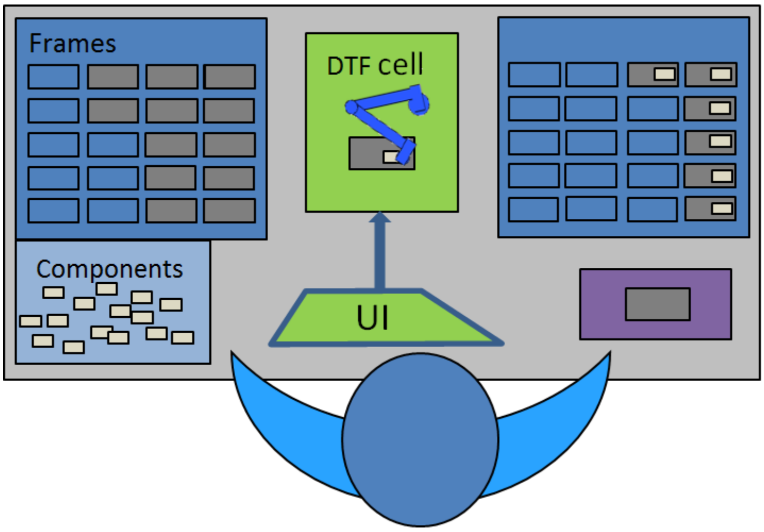



***Figure 2.*** *Tele-operated desktop factory unit – Automatic alignment (q.v. 6.1.1)*

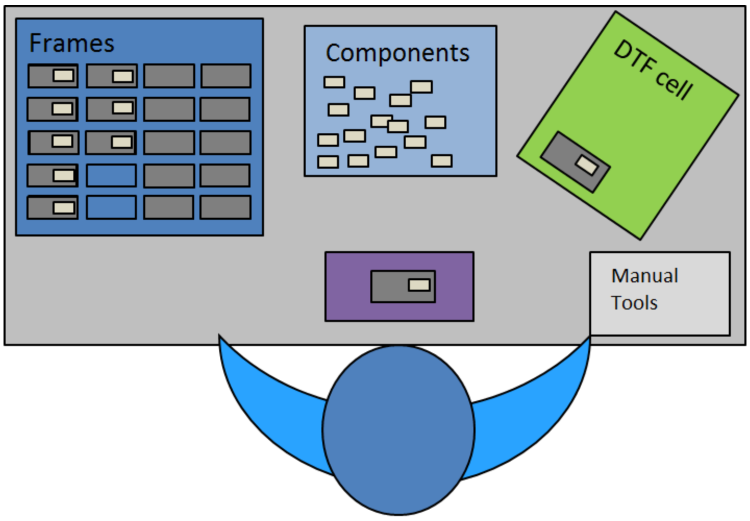



***Figure 3.*** *Automated assisted assembly – Automatic process (q.v. 6.3.2 and 6.3.3)*

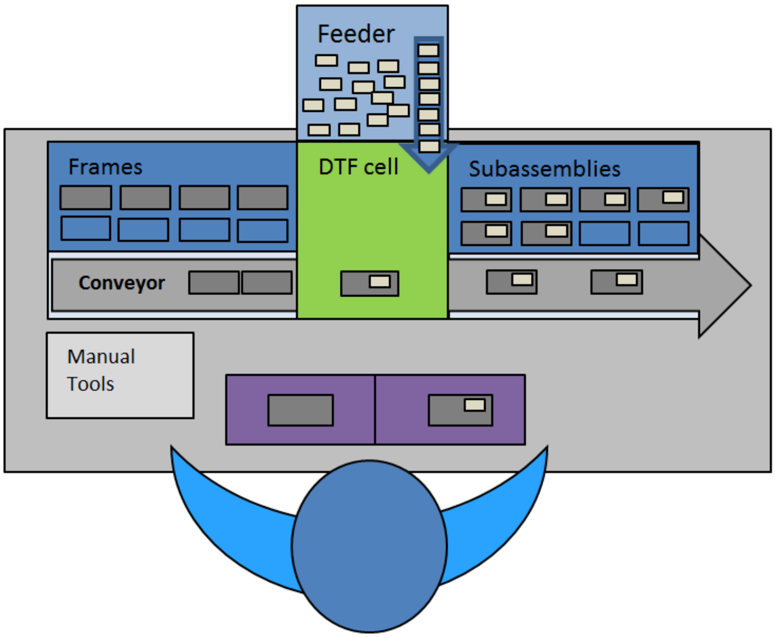



***Figure 4.*** *Small batch automation by trays and feeders*

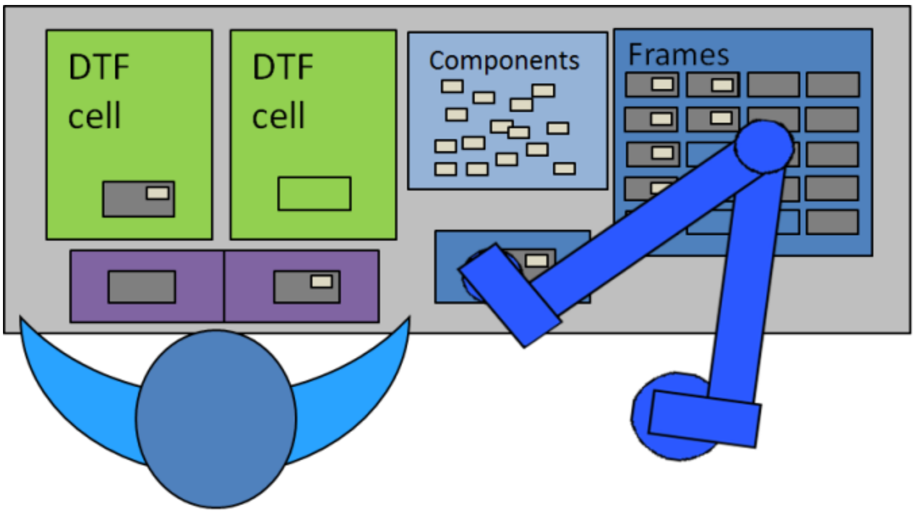



***Figure 5.*** *Small batch automation by a large-scale safety robot (q.v. 6.3.2)*

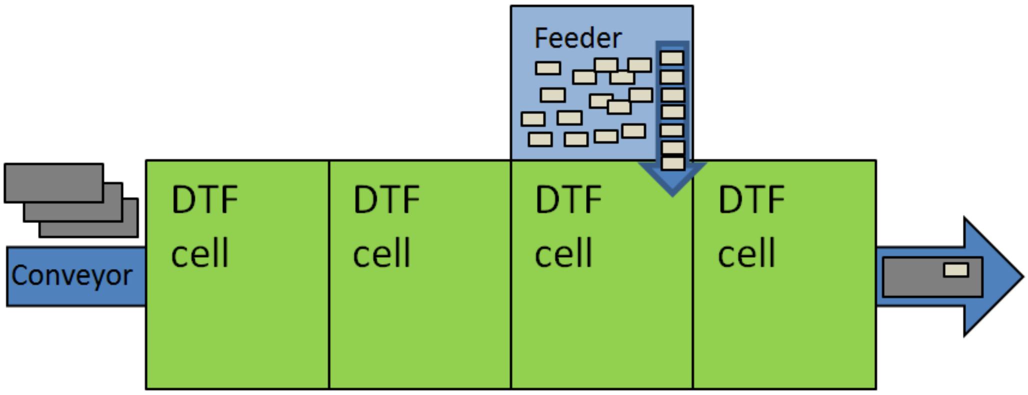



***Figure 6.*** *Multiple cells as offline process – Automated Inter-Cell Transfer*

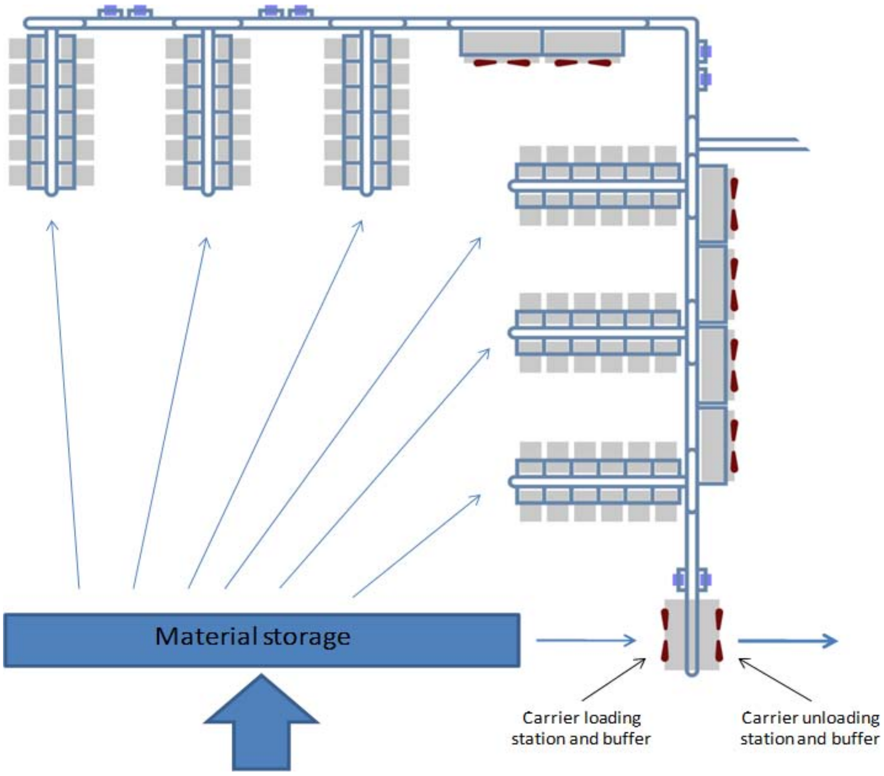



***Figure 7.*** *Inteligent factory automation system – Automated Inter-Cell Transfer (see Järvenpää, 2009, 2010)*

# APPENDIX 3: INVESTMENT CALCULATIONS

| Initial values | Option A | Option B | Both |
|---|---|---|---|
| Discount rate | | | 10% |
| Time of the investment (years) | | | 5 |
| The initial value of the investment | -€500,000 | -€600,000 | |
| Annual expenses | -€45,000 | -€20,000 | |
| Annual cashflow | €140,000 | €140,000 | |
| The final value of the investment | €250,000 | €250,000 | |

**Present value method**

| Present values | Option A | Option B | Excel formula |
|---|---|---|---|
| The initial value of the investment | €500,000 | €600,000 | |
| Annual expenses | €170,585 | €75,816 | =PV(10%,5,-20000) |
| Annual cashflow | €530,710 | €530,710 | =PV(10%,5,-140000) |
| The final value of the investment | €155,230 | €155,230 | =PV(10%,5,,-250000) |
| | | | |
| **Present value of returns** | €685,940 | €685,940 | =530710+155230 |
| **Present value of expenses** | €670,585 | €675,816 | =600000+75816 |
| **Net present value** | €15,355 | €10,125 | =685940-675816 |

**Equivalent annuity method**

| Annuities | Option A | Option B | Excel formula |
|---|---|---|---|
| The initial value of the investment | -€131,899 | -€158,278 | =PMT(10%,5,600000) |
| Annual expenses | -45,000 | -€20,000 | |
| Annual cashflow | €140000 | €140000 | |
| The final value of the investment | €40,949 | €40,949 | =PMT(10%,5,-25000) |
| | | | |
| **Cost annuity** | -€176,899 | -€178,278 | =-158278+(-20000) |
| **Return annuity** | €180,949 | €180,949 | =140000+40949 |
| **Equivalent annuity** | €4,050.63 | €2,670.88 | =-178278+180949 |

**Internal rate of return, IRR**

| | Option A | Option B | Excel formula |
|---|---|---|---|
| **Internal rate of return** | 11.0% | 10.5% | =RATE(5,(140000+ (-20000)), -600000,250000) |

**Payback method**

| | Option A | Option B | Excel formula |
|---|---|---|---|
| **Payback time (years)** | 5.26 | 5 | =600000/(140000+ (-20000)) |

# APPENDIX 4: TUT MICROFACTORY PROJECTS

| Duration | Project | Explanation | Budget | Companies |
|---|---|---|---|---|
| 2000-2002 | TOMI | Towards Mini and Micro Assembly Factories | 2,000,000€ | ABB, Festo, JOT Automation, Nokia, PerkinElmer Wallac, Perlos, PMJ automec, Suunto, Veslatec, VTI Hamlin, Merval |
| 2003-2005 | Beyond Mini Technologies | Precision and Micro Technologies for Future Processses and Devices | 662,752€ | Foxconn, Perlos, PMJ automec, VTI Technologies, Orbis, Festo, Elektrobit Automation, Tasowheel, ABB |
| 1.11.2005–31.12.2006 | M4 | Micro Meso Mechanical Manufacturing | 674,000€ | Corelase, Singulase, Festo, Nokia, ZET-Systems, Hermia, Bioretec, Vivoxid, Stick Tech |
| 1.1.2007 – 31.12.2007 | NEXT | Next Meneration Microfactories for Challenging Processes | 668,000€ | Corelase, Singulase, Festo, Nokia, ZET-Systems, Hermia, Bioretec, Vivoxid, Stick Tech |
| 1.9.2007 – 31.12.2009 | DESK | Integrated high-volume manufacturing and assembly of electronics | 741,000€ | Festo, Flexlink, Nokia, Master Automation Group, Vaisala, VTI Technologies |
| 1.1.2009 – 30.6.2010 | Mz-DTF | Building a desktop production systems | 533,400€ | Festo, Nokia, Master Automation Group, Vaisala |
| 1.9.2009 – 31.12.2011 | DeskConcept | The future and applications for desktop production systems | 493,000€ | Festo, Nokia, Master Automation Group, Vaisala, Wegera |

# APPENDIX 5: LIST OF INTERVIEWEES

***Table 1.*** *Interviewees – Academic members*

| Date | Name | Title | Organization | Location |
|---|---|---|---|---|
| 23.8.2011 | Ilari Marstio & Timo Salmi | Research Scientists | VTT | Espoo, Finland |
| 20.9.2011 | Andreas Hofmann | Researcher | KIT | Karlsruhe, Germany |
| 21.9.2011 | Phillipp Kobel | Doctoral Student | EPFL (LSRO) | Lausanne, Switzerland |

***Table 2.*** *Interviewees – Equipment providers*

| Date | Name | Title | Organization | Location |
|---|---|---|---|---|
| 10.8.2011 | Mika Laitinen | Sales Manager | Fastems | Tampere, Finland |
| 19.8.2011 | Seppo Kauppi | Project Manager | Wegera | Oulu, Finland |
| 25.8.2011 | Kalle Härkönen | Operation Direction | Biohit | Helsinki, Finland |
| 26.8.2011 | Vesa Hirvonen | Technology Manager | MAG | Vantaa, Finland |
| 22.9.2011 | Alain Coroudrey | CEO | Asyril | Villaz-St-Pierre, Switzerland |
| 23.9.2011 | David Hériban | CEO | PercipioRobotics | Bensançon, France |

***Table 3.*** *Interviewees – Component providers*

| Date | Name | Title | Organization | Location |
|---|---|---|---|---|
| 25.8.2011 | Jukka Kenttämies | Product Group Manager | Festo Oy | Vantaa, Finland |
| 12.9.2011 | Cristoph Hanisch | Technology Manager | Festo AG | Tampere, Finland |

***Table 4.*** *Interviewees – Users or potential users of miniature production systems*

| **Date** | **Name** | **Title** | **Organization** | **Location** |
|---|---|---|---|---|
| 16.8.2011 | Harri Heino | R&D Director | Bioretec | Tampere, Finland |
| 23.8.2011 | Tomi Pietari | Head of Production Technology | Vaisala | Vantaa, Finland |
| 24.8.2011 | Teemu Suominen | Supply Chain Engineering Manager | Suunto | Vantaa, Finland |
| 25.8.2011 | Kalle Härkönen | Operation Direction | Biohit | Helsinki, Finland |
| 02.9.2011 | Jari Luotonen | Senior Manager | Nokia | Salo, Finland |
| 19.9.2011 | Andy Zott | Technology Manager | Nokia | Ulm, Germany |

***Table 5.*** *Interviewees – Retailers/ product personalization*

| **Date** | **Name** | **Title** | **Organization** | **Location** |
|---|---|---|---|---|
| 06.9.2011 | Pekka Tirkkonen | Production Manager | Verkkokauppa | Helsinki, Finland |

***Table 6.*** *Interviewees – 3D printing and home fabrication*

| **Date** | **Name** | **Title** | **Organization** | **Location** |
|---|---|---|---|---|
| 23.8.2011 | Eero Heurlin | Member | Helsinki Hacklab | Helsinki, Finland |

# APPENDIX 6: LIST OF MINIATURIZED PRODUCTION SYSTEMS



## PREFACE

This is a short summary of miniaturized production systems. It includes different academic concepts and commercial units. Micro and desktop factories; small-size machining unit; small-size robotic, assembly and process cells; as well as desktop-size 3D printers and rapid prototyping units are included.

The list has been gathered up because there is no all-inclusive source available. However, some good summaries have been published (see e.g. Okazaki et al., 2004).

The list is not complete. The author is aware that also other related academic concepts have been created as well as many additional commercial units have been developed. However, it includes many of the concepts and machines usually cited in the related literature. The “Year” refers to the year a given concept or product has been published, according to the author’s knowledge.

*Tampere, 6.1.2012*
*Anssi Nurmi*

## ABBREVIATIONS OF INSITUTIES AND LABORATORIES

| | |
|---|---|
| AIST | Agency of Industrial Science and Technology (Japan) |
| AMRI | Advanced Manufacturing Research Institute (Japan) |
| CMU | Carnegie Mellon University (Pittsburgh, USA) |
| CSEM SA | *Centre Suisse d'Electronique et de Microtechnique S.A.* [1] (Switzerland) |
| DTF | Desktop Factory Study Group (Japan) |
| EPFL | *École Polytechnique Fédérale de Lausanne* [1] (Lausanne, Switzerland) |
| FEMTO-ST | *Franche-Comté Electronique, Mécanique, Thermique et Optique - Sciences et Technologies* [1] (Besançon, France) |
| Frauenhofer IPA | *Fraunhofer-Institut für Produktionstechnik und Automatisierung* [2] (Stuttgart, Germany) |
| KIMM | Korea Institute of Machinery & Materials (Daejeon, Korea) |
| KIT | *Karlsruher Institut für Technologie* [2] (Karlsruhe, Germany) |
| LPM | *Laboratoire de Production Microtechnique* [1], a laboratory of EPFL (Switzerland) |
| LSRO | *Laboratoire de Systèmes Robotiques* [1], a laboratory of EPFL (Switzerland) |
| MCC | Micromachine Center (Japan) |
| MEL | Mechanical Engineering Laboratory, a laboratory of AIST (Japan) |
| new AIST | National Institute of Advanced Industrial Science and Technology (Japan) |
| TIRI | Tokyo Metropolitan Industrial Technology Research Institute (Japan) |
| TUT | Tampere University of Technology (Finland) |
| UIUC | University of Illinois at Urbana–Champaign (Illinois, USA) |
| UNAM | *Universidad Nacional Autónoma de México* [3] (Mexico) |
| VTT | Technical Research Centre of Finland (*Valtion teknillinen tutkimuslaitos*) [4] |

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[1] French abbreviation
[2] German abbreviation
[3] Spanish abbreviation
[4] Finnish abbreviation

# 1. MICRO AND DESKTOP FACTORIES

***Table 1.1.*** *Traditional academic microfactory concepts*

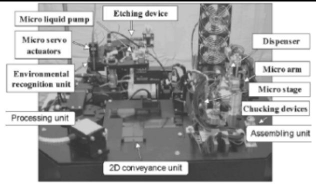
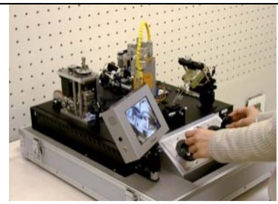
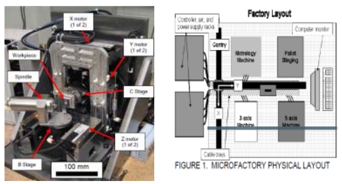
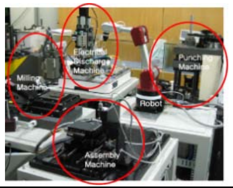
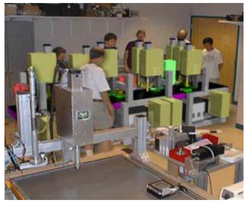
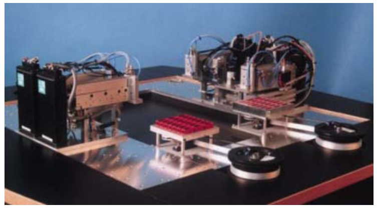
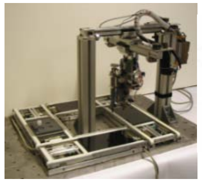
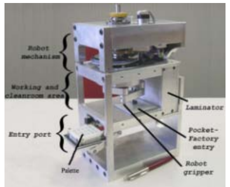
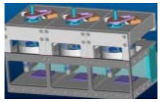
| Year | CC | Concept | Institute | Source | Picture |
|---|---|---|---|---|---|
| 1994 | JP | **Microfactory by MMC or Experimental Microfactory System**<br>• 600x650x750mm, working area of 1cm$^3$<br>• Object size <10mm, weight <2g<br>• Conveyor, processing and assembly units | **MMC**<br>(& 7 companies) | Ataka, 1999;<br>Ogawa, 2000 |  |
| 1998 | JP | **Portable Microfactory or Desktop Machining Microfactory**<br>• 625x490x380mm, 34kg<br>• A lathe, a milling machine, a press, a transfer arm and a micro manipulator | **AIST**<br>(MEL, Mechanical Engineering Laboratory ) | Kitahara et al., 1998;<br>Tanaka, 2001 |  |
| 2000 | FIN | **TOMI Microfactory**<br>• 1800x500mm base<br>• 500x500mm modules<br>• A case product: a planetary gearhead | **TUT**<br>(Department of Production Engineering) | Tuokko et al., 2000;<br>Tuokko, 2002 |  |
| 2006 | USA | **Automated Illinois Microfactory**<br>• 900x900mm vibration isolation table<br>• Metrology station, 3 and 5-axis machining units and a computer-based interface | **UIUC** (Dep. of Mechanical and Industrial Engineering | Honegger et al., 2006a;<br>Honegger et al., 2006b |  |
| 2006 | KR | **Mosaic**<br>• Micro milling machine, electrical discharge machine, manipulator, assembly machine and  punching robot | **KIMM**<br>(Intelligent Machine Systems Research Center) | Park et al., 2007 |  |

***Table 1.2.*** *Modular academic microfactory concepts*

| Year | CC | Concept | Institute | Source | Picture |
|---|---|---|---|---|---|
| 2001 | USA | **AAA, Agile Assembly Architechture**<br>• Based on "minifactory" segments<br>  o Modular base frame, planar table, precision part feeders and overhead 3DOF manipulator | **CMU**<br>(The Robotics Institute) | Rizzi et al., 2001 |  |
| 2001 | GER | **AMMS, Advanced Modular Microassembly System**<br>• 800x800mm, XY accuracy 20µm<br>• 600x400mm planar table, moving conveyors and fixes process modules | **Frauenhofer IPA** | Gaugel & Bengel, 2001;<br>Gaugel et al., 2004 |  |
| 2004 | FIN | **ABAS Desktop Platform**<br>• Agent based architecture<br>• Material handling system has been constructed as pilot project | **TUT**<br>(Department of Production Engineering) | Lastra, 2004;<br>Jokinen, 2006;<br>Jokinen & Lastra, 2007 |   |
| 2005 | CH | **Microbox Pocket-Factory**<br>• 1dm$^3$ clean working space (ISO 5 class)<br>• Entry port, 4DOF scara robot, sensors, airflow generator and filtration system | **EPFL** (LSRO, Laboratoire de Systèmes Robotiques) | Verettas et al., 2005 |   |
| 2005 | FIN | **TUT Microfactory**<br>• 300x200x220mm, working space 180$^3$mm<br>• Aluminium body, control cabinet, integrated cleanroom system, standard interfaces and multiple process modules | **TUT**<br>(Department of Production Engineering) | Heikkilä et al., 2007;<br>Heikkilä et al., 2010 |   |

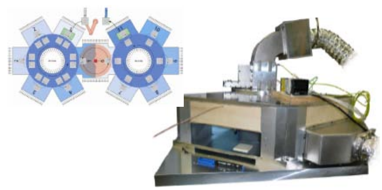
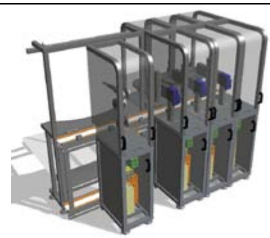
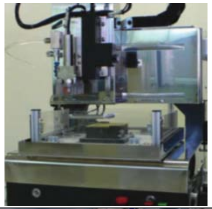
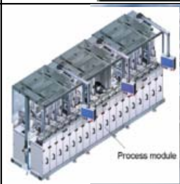
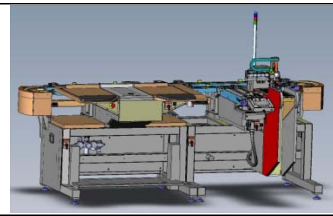
| | | | | | |
|---|---|---|---|---|---|
| 2008 | JP | **Module-Based Microfactory**<br>• 500x800x1200mm<br>• Module includes PLC, transfer unit, process unit and connections | **AMRI** &<br>new AIST | Nakano et al., 2008;<br>Ashida et al., 2010 |  |
| 2010 | CH | **Rotary Assembly Line**<br>• Central unit: air inlet, rotary table for standard 2” trays and module interfaces<br>• Modules: working area, space for robot, air outlet, product inlets/outlets | **EPFL** (LSRO, Laboratoire de Systèmes Robotiques) | Kobel & Clavel, 2010 |  |
| 2011 | FIN | **Desktop Asesmbly**<br>• Floorstanding<br>• Intelligent conveyor system, standard base modules and specific process moduees | **VTT**<br>(& multiple companies) | see VTT, 2011 |  |

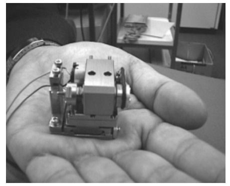
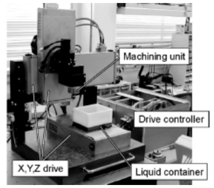
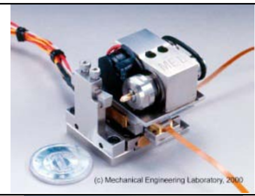
***Table 1.3.*** *Commercialized micro and desktop factories*

| **Year** | **CC** | **Product** | **Company** | **Source** | **Picture** |
|---|---|---|---|---|---|
| 2003 | JP | **Desktop Factory DTF®**<br>• Multiple processes, e.g. cleaning, coating, screwing measuring and assembly<br>• Module width 170 mm | **NIDEK Sankyo Co.** | see Tuneda, 2005 |  |
| 2003 (2008) | JP | **Multi-Pro**<br>• Versatile desktop machine platform<br>• E.g. laser processing, precision processing, EMD, jig grinder, CAM system (<8 Axis)<br>• 476x477x625 mm | **Takashima Sangyo Co.** | see Endo, 2010;<br>Takashima Sangyo, 2011 |  |
| 2007 | GER | **Lean Desktop Factory**<br>• Modular floor standing 'desktop' assembly system<br>• Module width 220 mm | **Bosch Rexroth AG** | Klemd, 2007 |    |
| 2010 | FIN | **MAG Lean**<br>• 3/4-Axis multi-function automation cell, e.g. pick and place, and screwing<br>• 250x500x500mm, 25-40kg | **MAG, Master Automation Group** | MAG, 2010 |   |
| 2011 | GER | **microFLEX**<br>• 800x1000mm for processes, in/out buffers<br>• Manual – semi-automatic – fully automatic<br>• Logistics based on 80mm trays and RFID<br>• 1200x800x800mm | **IEF Werner GmbH** | Hofmann et al., 2011;<br>IEF Werner GmBH, 2011 |  |

| | | | | | |
|---|---|---|---|---|---|
| 2011 | FIN | **JOT Lean**<br>• Multifunction desktop cell (e.g. pick and place, dispensing, screwing, plasma treatment)<br>• 533x600x710 mm or 333x600x710 mm | **JOT Automation** | JOT Automation, 2011 |  |
| 2012 | USA | **Nexar®**<br>• Modular high throughput liquid handling system for sub-microliter volumes<br>• Process and scans samples in a tape<br>• Modules 640x813x287 mm | **Douglas Scientific** | Douglas Scientific, 2012 |  |

## 2. SMALL-SIZE MACHINING UNITS

***Table 2.1.*** *Academic miniaturized machining units*

| Year | CC | Concept | Institute | Source | Picture |
|---|---|---|---|---|---|
| 1996 | JP | **Microlathe**<br>• 32x25.0x30.5 mm, 0.1 kg<br>• 10,000 rpm, 1.5 W<br>• Accuracy 1.5 µm, min diameter 60 µm | **AIST**<br>(MEL, Mechanical Engineering Laboratory) | Kitahara et al, 1998;<br>see Okazaki et al., 2004 |  |
| 1999 | JP | **Multifunction desktop machine**<br>• 557x604x655mm, 80kg<br>• 5 changeable machining units: high, middle and low speed spindles, laser irradiationer and piezoelectric actuator | **AIST**,<br>new AIST &<br>Disco Co. | Kurita et al., 2001 |  |
| 2000 | JP | **NC Microlathe**<br>• See Microlathe above<br>• Additional precision digital control system | **AIST** & new AIST<br>(MEL, Mechanical Engineering Laboratory) | Okazaki & Kitahara, 2000;<br>see Okazaki et al., 2004 |  |
| 2001 | JP | **Desk-Top NC Milling Machine, 200krpm**<br>("El Chuchito")<br>• 450x300x380mm, 120W<br>• 0.1µm control system resolution | **new AIST**,<br>TIRI &<br>Chiba University | Okazaki et al., 2001 |  |
| 2004 | JP | **Desk-Top Milling Machine, 300krpm**<br>• See "El Chuchito" above<br>• 480x480x470mm, 42kg, 400W<br>• Linear XY stage | **new AIST** | Okazaki, 2004 |  |

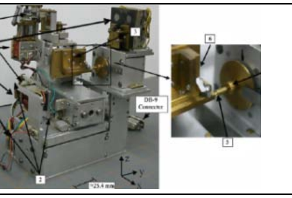
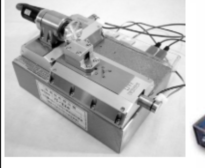
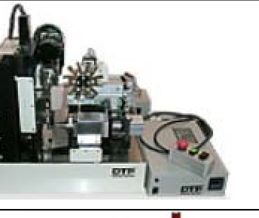
| | | | | | |
|---|---|---|---|---|---|
| 2004 | MX | **Mexican First Generation MMT**<br>• Multiple generations<br>• From 130x160x85mm<br>• Based on stepping motors | **UNAM**<br>(Laboratory of Micromechanics and Mechatronics) | Ruiz-Huerta et al., 2004 |  |

***Table 2.2.*** *Commercial small-size stand-alone machining units*

| **Year** | **CC** | **Product** | **Company** | **Source** | **Picture** |
|---|---|---|---|---|---|
| 2002 | JP | **Nanowave MTS2C**<br>• NC precision lathe<br>• Base 150x100 mm | **Nano Corporation** | Iijima, 2002;<br>Nano Co., 2005a |   |
| 2003 | JP | **Multi-Pro**<br>• Versatile 3-axis desktop machine platform (e.g. grinding, EMD and laser processes)<br>• 476x477x625mm, 160kg | **Takashima Sangyo Co.** | see Endo, 2010;<br>Takashima Sangyo, 2011 |  |
| 2003 | JP | **Multi-function Turning Center**<br>• Small-size lathe/mill with tool exchanger<br>• A3 size (420x295 mm) | **DTF Consortium** | see DTF, 2011 |  |
| 2004 | JP | **TRIDER-X**<br>• 4 Axes grinder<br>• 560x580x650mm, 120kg | **Rinken Co.** | Lin et al. 2004 |  |

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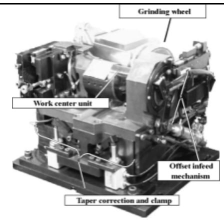
|---|---|---|---|---|---|
| 2004 | JP | **Desktop Milling Machine**<br>• Micro press and laser machining equipment commercialized as well | **PMT Co.** | see Okazaki et al., 2004 |  |
| 2004 | JP | **Cylindrical cells**<br>• Turning and grinding<br>• Base 200x200 mm, 43kg | **SII Co.** | see Okazaki et al., 2004 |  |
| 2005 | JP | **Nanowave MTS3**<br>• CNC Precision Lathe<br>• Base 200x300 mm<br>• Positioning accuracy of 1µm | **Nano Corporation** | Nano Co., 2005b |  |
| 2005 | JP | **Nanowave MTS4**<br>• CNC Precision Lathe<br>• Base 220x320 mm<br>• Positioning accuracy of 5µm | **Nano Corporation** | Nano Co., 2005c |  |
| 2005 | JP | **Nanowave MTS5/MTS6**<br>• CNC Precision Milling Machine<br>• Base 260x324 mm, 43kg<br>• Positioning accuracy of 1µm | **Nano Corporation** | Nano Co., 2005d |  |

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|---|---|---|---|---|---|
| 2008 | USA | **G4-ULTRA CNC**<br>• 3/4/5-Axis micromachining<br>• 1 $m^2$ footprint | **Atometric Inc.** | Atometric Inc., 2008 |  |
| 2008 | USA | **Microlution 363-S**<br>• 3-Axis micro-mill/grill<br>• 610x610x1372 mm | **Microlution Inc.** | Microlution Inc., 2007 |  |
| 2008 | USA | **EM203**<br>• Micro-EDM Micro Grinding<br>• 710x835x810mm, 325kg;<br>• Maximum mass of work piece: 5.5kg<br>• 200x200mm working area | **SmalTec** | SmalTec, 2008a |  |
| 2008 | USA | **GM703**<br>• Micro-EDM Nano Grinding<br>• 500x500x565mm, 125kg;<br>• Maximum mass of work piece: 2kg<br>• 50x50 mm working area | **SmalTec** | SmalTec, 2008b |  |
| 2009 | USA | **MM903**<br>• Micro machine<br>• 925x850x925mm, 225kg<br>• Maximum mass of work piece: 55kg<br>• 200x200 mm working area | **SmalTec** | SmalTec, 2009 |  |

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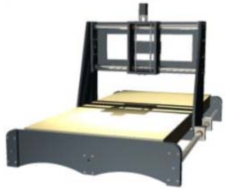
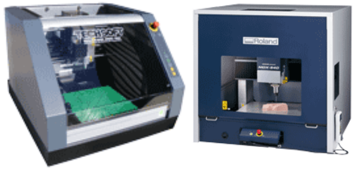
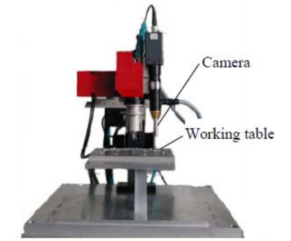
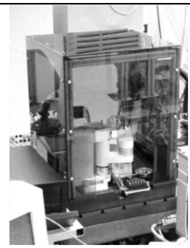
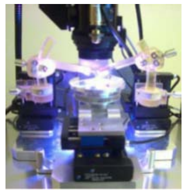
|---|---|---|---|---|---|
| 2009 | JP | **Micro mill CVN-2000**<br>• 4-Axis CNC mill<br>• 370x374x642mm, 95kg | **Enomoto Kogyo Co.** | Enomoto Kogyo, 2009 |  |
| 2010 | GER | Impression line: **cam4-02**, **cam5-02**, **cam4-K1** and **cam4-K2**<br>• 4/5-Axis CNC machine<br>• E.g. dental & jevellery<br>• 400x385x410mm, 40kg or 620x530x515mm, 80kg | **VHF camfacture AG** | vhf camfacture, 2010 |  |
| 2011 | FIN | **Kolibri**<br>• 3-5/(6)-Axis CNC machine<br>• Authentic CNC<br>• Automatic tool changer<br>• 498x740x910mm, 700kg 748x740x910mm, 750kg | **Wegera** | Wegera, 2011 |  |

*Table 2.3.* *Commercial small-size hobby and educational machining units*

| Year | CC | Product | Company or community | Source | Picture |
|---|---|---|---|---|---|
| Since 1999 | USA | **CNC tools for hobbyists**<br>• From $550 | **HobbyCNC** | HobbyCNC, 2011 |  |
| 2010 | UK | E.g. **PRO II MDX-540E** and **RotoCAMM MDX-40AE**<br>• ¾-Axis educational CNC machine<br>• 669x760x554mm, 66kg or 1060x1100x978mm,170kg<br>• $4695 ... $8056 or $13995 ... $18645 | **Techsoft UK** | TechSoft UK, 2010a<br>TechSoft UK, 2010b |  |
| 2011 | JP | **iModeal iM-01**<br>• Affordable 3D hobby mill<br>• 214x200x205mm, 1.7kg<br>• Suitcase package<br>• $500 … $5000 | **Roland DG Co.** | Rolanda DG Co., 2011a;<br>Rolanda DG Co., 2011b |  |
| 2011 | JP | Low-priced machining units, e.g. **BLACKII 1510**<br>• Educational CNC machine<br>• Base 150x100mm, 8.3kg<br>• From $1279 | **Originalmind** | Orginalmind, 2011 |  |

## 3. SMALL-SIZE ROBOTIC, ASSEMBLY AND PROCESS CELLS

***Table 3.1.*** *Academic miniaturized robotic, assembly or process cells*

| Year | CC | Concept | Institute | Source | Picture |
|---|---|---|---|---|---|
| 2002 | CH | **Flexible Microassembly Cell**<br>• Working volume 150x150x150 mm<br>• Vision system<br>• Low and high-resolution models<br>o 4DOF, a resolution of 5µm<br>o 6DOF, 0.5µm + 3DOF robot | **EPFL**<br>(LPM, Laboratoire de Production Microtechnique) | Koelemeijer Chollet et al., 2002 | <br>*Figure 4 - Robot 4 axes and 5 µm resolution* |
| 2003 | GER | **µFemos**<br>• 600x600x500mm (A3 paper size)<br>• 4DOF axis system (XYZ and rotation)<br>• Developed for precision assembly of an optical distant sensor | **KIT**<br>(& IEF Werner GmbH) | Bär, 2006 |   |
| 2004 | FIN | **Mini assembly cell**<br>• For the assembly of mini-sized planetary gearheads<br>• Part of TOMI microfactory concept<br>• Base 500x500 mm | **TUT** | Uusitalo et al., 2004 |   |
| 2008 | TR | **Versatile and Reconfigurable Microassembly Workstation**<br>• Two 3DOF micromanipulator stages<br>• 3DOF sample positioning system<br>• Vision system with 3DOF and 2 cameras | **Sabanchi University**, Gebze Institute of Technology | Kunt et al., 2008 |   |

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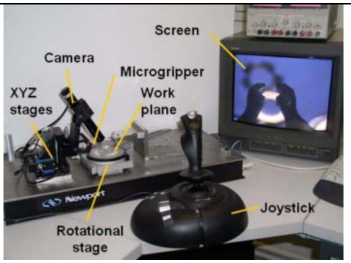
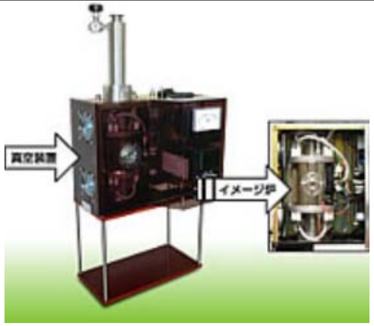
|---|---|---|---|---|---|
| 2008 | FR | **Flexible Micro-Assembly System with Automated Tool Changer**<br>• Tele-operated<br>• XYZ positioning, camera, piezoelectric gripper with tool changer<br>• Positioning accuracy: about 3µm | **FEMTO-ST** (Department of Automatic Control and Micro-Mechatronic Systems) | Clévy et al., 2008 |  |
| 2011 | GER | **Robotic Systems for High Throughput Bio Analytics**<br>• Desktop-size robotic cell for automation of bio analytics (sorting zebrafishes)<br>• Machine-vision based pipetting<br>• 3-Axis (XYZ) | **KIT** (AIA, Institut für Angewandte Informatic) | Pfriem et al., 2011 |  |

***Table 3.2.*** *Commercialized small-size stand-alone process cells*

| **Year** | **CC** | **Product** | **Company** | **Source** | **Picture** |
|---|---|---|---|---|---|
| 2005 | JP | **Ultra Compact Hot Embossing Machine**<br>• Floorstanding | **DTF Consortium** | see DTF, 2011 |  |

| | | | | | |
|---|---|---|---|---|---|
| 2005 | JP | **Desktop Nickel Plating Machine**<br>• 812x303x300 mm | **DTF Consortium** | see DTF, 2011 |  |
| 2007 | UK | Fully automated ELISA workstations **DS2™** and **DSX™**<br>• Automated analysing systems<br>• E.g. diseases, blood-chemistry and drugs<br>• 540x680x660mm, 100kg or 1060x910x800mm, 136kg | **DYNEX Technologies** | DYNEX Technologies, 2007a<br>DYNEX Technologies, 2007b |  |
| 2009 | IT | Desktop-size chemistry analysers, e.g. **Keylab** and **Global240**<br>• Automated random access automatic analyzers<br>• 550x600x750mm, 50 kg or 580x600x730mm | **BPC BioSede SRL** | BPC BioSede SRL, 2009a<br>BPC BioSede SRL, 2009b |  |
| 2010 | USA | Nanomolding machine **Sesame**<br>• Injection moulding (medical solutions)<br>• Floorstanding<br>• Materials e.g.: bioabsorbable polymers, thermoplastic and silicone rubber<br>• Applications e.g.: overmolded polymers, electronics and radiopaque markers | **Medical Murray Inc.** | Medical Murray, 2011 |  |

***Table 3.3.*** *Commercialized small-size stand-alone robotic cells*

| Year | CC | Concept | Institute | Source | Picture |
|---|---|---|---|---|---|
| 2009 | CH | **Asyfeed Pocket**<br>• Flexible multi-function robot cell, e.g. assembly palletizing and sorting<br>• 400x400x500mm,<br>**Asyfeed Desktop** was 800x800x2250 mm | **Asyril** | see Asyril, 2010 |  |
| 2010 | FIN | **J505-62**<br>• Desktop screwing cell<br>• 495x754x962 mm | **JOT Automation** | JOT Automation, 2010a |  |
| 2011 | FIN | **Roboline**<br>• Desktop cell for automated pipetting<br>• 347x346x381mm, 11.5kg | **Biohit Oyj** | Biohit, 2011 |  |
| 2011 | CH | **Asyfeed Pocket**<br>• Flexible multi-function robot cell, e.g. assembly palletizing and sorting<br>• 400x400x500mm | **Asyril** | Asyril, 2011 |  |

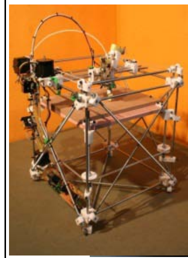
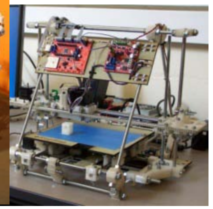
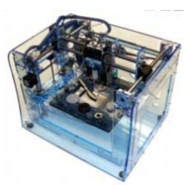
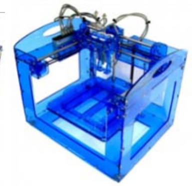
## 4. DESKTOP-SIZE 3D PRINTERS AND RADIP PROTOTYPING UNITS

***Table 4.1.*** *Examples of commercial desktop-size industrial 3D printers*

| Year | CC | Product | Company | Source | Picture |
|---|---|---|---|---|---|
| 2009 | USA | **uPrint** and **uPrint plus**<br>• ABS*plus*™ material (own)<br>• Layer thickness 0.254 mm<br>• 76kg<br>• 203x152x152 mm or 203x203x152 mm<br>• From $14,900 or $19,900 | **Dimension (Stratasys)** | Dimension, 2010 |  |
| 2009 | IL | **SD300 Pro**<br>• PVC material (own)<br>• Layer thickness 0.168 mm<br>• 160x210x135 mm, 45kg<br>• From €2,950 (€14,950 plug-and-print) | **Solido** | Solido LTD, 2009 |  |
| 2009 | USA | **V-Flash**<br>• FTI-GN material<br>• Layer thickness 0.102 mm<br>• 660x685x787 mm, 66kg<br>• From $9,900 | **3D Systems** | 3D Systems Inc., 2011b |  |
| 2010 | USA | **ModelMaker**<br>• 3D foam cutter (e.g. for architects)<br>• 635x635x330mm<br>• $12,000 | **2BOT physical Modeling Technologies** | 2BOT physical Modeling Technologies, 2010 |  |

| | | | | | |
|---|---|---|---|---|---|
| 2010 | USA | **Objet24** and **Objet30**<br>• Versatile materials<br>• Layer thickness 0.028 mm<br>• 93kg<br>• 234x193x149 mm or 294x193x149 mm<br>• From $20,000 or $40,000 | **Objet** | Objet, 2010a<br>Objet, 2010b |  |
| 2011 | USA | **Objet260 Connex**<br>• Multi-Material printing<br>• 870x735x1200mm, 264kg | **Objet** | Objet, 2011 |  |
| 2012? | USA | **Desktop Factory 125ci**<br>• Layer thickness 0.254 mm<br>• 508x635x508 mm, 50kg<br>• From $4,995 | **Desktop Factory** | 3D Systems Inc., 2011a |  |

*Table 4.2. Academic miniaturized robotic, assembly or process cells*

| Year | CC | Printer | Company or community | Source | Picture |
|---|---|---|---|---|---|
| 2006-2010 | UK | **RepRap 0.2**, **Darvin**, **Mendel**, **Huxley** and **Prusa Mendel**<br>• Open source do-it-yourself 3D printers<br>• 370x300x255mm, 4kg … 600x520x650mm, 14kg<br>• $400 … $650 | **RepRap** (Wiki) | RepRap, 2011 |   |
| 2006-2010 | USA | **Model 1** and **Model 2**<br>• Open source/ commercial 3D two-component printer<br>• 410x460x470mm<br>• $1600 … $2290 | **Fab@Home** (Wiki) | Fab@Home, 2010<br>Fab@Home, 2011 |   |
| 2009-2010 | USA | **CupCace CNC** and **Thing-O-Matic CNC**<br>• Commercial hobby 3D printer<br>• 350×240×450mm, 5kg or 300×300×410mm, 5kg<br>• $649/$950…$1299/$2500 | **MakerBot** | MakerBot, 2011 |   |
| 2009-2010 | UK | **The RapMan 3.1** and **3DTouch**<br>• RepRap based commercial 3D printer (for education)<br>• 650x570x820mm, 17kg<br>• $494 … $1992 or $3210 ... $4015 ($=£0.62) | **Bits from Bytes** | Bits From Bytes, 2011 |   |