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Dimensions for reconfiguration decision-making and concept for feasibility analysis of reconfigurable pilot lines in industry, research and education

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Abstract

Reconfigurable manufacturing systems offer possibilities for customized flexibility on demand that aims for achieving cost-effective and rapid system changes. However, constantly changing customer requirements, increasing number of product variants, smaller batch sizes, and new emerging technologies pose challenges for the design of such systems. Especially smaller companies have major difficulties to develop even simple, cost-effective, and flexible manufacturing systems. There is an obvious need for low-threshold reconfigurable test-before-invest pilot systems which configuration can be changed according to current need. In such pilot systems companies can test new manufacturing technologies and concepts before investment decisions. While there are many articles for developing reconfigurable manufacturing systems, there are limited amount of research done for piloting environment perspective. Objective of this study is to present concept for the reconfigurable pilot line which fulfills frequently changing requirements of industry, research, and education by changing configuration of the system. Dimensions for reconfiguration decision-making are outlined for these systems. Based on these dimensions, evaluation criteria for feasibility analysis are defined to assess whether the reconfiguration concept is feasible from technical, resource, and economical point of views.

Keywords: Reconfigurable Pilot System; Piloting Environment; Reconfiguration Decision-Making; Feasability Analysis; Analytic Hierarcy Process

1. Introduction

Today's manufacturing companies are facing radical challenges: frequently changing customer requirements, high-quality products, increasing customization, flexible batch sizes, and shorter product life cycles [1]. To cope with these critical challenges, there is a need for agile, adaptive, and rapidly responding production systems [2]. In practice, this means systems which can change their functionalities and structure when needed [3]. To solve this problem, Koren et al. [4] presented the concept of a reconfigurable manufacturing system (RMS) already in the late 1990s: '...designed at the outset for rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality within a part family in response to sudden changes in market or in regulatory requirements'.

Since the first definition of RMS there have been published countless number of articles on this topic as seen from multiple literature review articles [1, 5-8]. Publications have mainly focused on to industrial production cases of RMS [1, 5-8] and reconfigurable manufacturing tools (RMTs) [9, 10]. Covered topics include definitions and design guidelines for RMS key characteristics [5-8], methods for RMS layout design [11] and techniques for RMS product family formation [12, 13]. There are also few articles which either defines assessment methods for reconfiguration scheme evaluation [14] or proposes ranking methods to rank alternative reconfiguration plans [15]. However, presented evaluation methods assume that there are already detailed existing plans for reconfiguration. There is an obvious need for early-stage reconfiguration assessment criteria: what are the technical, economical and resource requirements for a concept phase reconfiguration decision-

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making. Based on the criteria, method for initial reconfiguration feasibility analysis can be proposed.

During the last decade there have been research around piloting environments. In these systems companies can produce and validate pilot products in order to allow rapid implementation of these pilot products in their own manufacturing systems. After this piloting environments may be closed or taken down to rebuild those from the beginning. These systems are typically quite expensive and hard to access. [16] This isn't sustainable solution. For small and medium-sized enterprises (SMEs) there is a need for academy driven reconfigurable pilot lines (RPLs). These are pre-commercial test-before-invest production or prototyping environments which enable learning through experimentation in new product, service, and business development. RPLs support SMEs to test their products and manufacturing concepts before final investment decisions and to get familiar with new emerging technologies. By changing configuration of a pilot line, SMEs from different sectors can utilize these easy to access, low-threshold, and cost-effective prototyping environments. Academy driven RPLs don't fulfill only the needs of industrial research, development, and innovation (RDI) but also the needs of academic research and education.

This article presents definition for the RPL, dimensions for an early-stage reconfiguration decision-making and a concept for early-stage reconfiguration feasibility analysis: is the suggested reconfiguration concept feasible from the technical, resource and economical point of views. Structure of the article is as follows. In Section 2 literature review highlights the latest research related to the RMS, especially from the reconfiguration assessment point of view. In Section 3 dimensions for the reconfiguration decision-making and concept for the early-stage reconfiguration feasibility analysis are presented. In Section 4 an example reconfigurable pilot line is presented, and the proposed reconfiguration feasibility analysis concept is tested within this system. Sections 5 and 6 covers discussion of the results, concludes the research and provides guidelines for future work.

2. Literature review

Recently, the focus of RMS research has shifted from the definition, key characteristics, and fundamentals of RMS towards to optimizing the design of RMS from different perspectives. Yelles-Chaouche et al. [17] presented several different performance objectives and optimization methods for RMS. Farid [18] defined mathematical models to measure performance of the key characteristics of RMS. Moghaddam et al. [19] presented a two-phase method to optimize reconfiguration transformation from system's scalability and cost perspectives. Puik et al. [14] utilized axiomatic design methodology for the assessment of reconfiguration schemes from the resources and lead time perspectives. Colledani and Angius [20] proposed an integrated modelling framework and methodology for modular plug-and-produce production systems. Methodology utilizes lot sequence optimization to maximize system service level, and stochastic lot completion time distribution analysis for production and reconfiguration planning [20]. Sabioni et al. [21, 22] have focused on to the concurrent optimization of modular products and RMS's configurations. They introduced an optimization approach that integrates product configuration design with process planning and RMS layout configuration design based on customer-specific requirements [21].

Unforeseen production conditions of the future are one of the latest research topics in RMS design. Prasad and Jayswal [23] used Shannon entropy and Multi Attribute Range Evaluation (MARE) to evaluate product scheduling in RMS. Shannon entropy calculates weights of the used decision criteria and MARE ranks the criteria based on the calculated uncertainty of the decision criteria [23]. Liu et al. [24] presented a two-stage optimization model to address the demand for uncertain production in initial reconfigurable transfer system design and in its necessary reconfigurations. Huang et al. [25] proposed dynamic complexity-based decision method to identify appropriate time for reconfiguration.

There are some publications that utilize either analytic hierarchy process (AHP) or other ranking methods to make RMS reconfiguration decisions. Wang et al. [15] generated quantitative evaluation index models which reflect key characteristics of RMS. Alternative reconfiguration schemes were ranked based on the calculated evaluation index values [15]. Both Maier-Speredelozzi and Hu [26] and Park [27] applied AHP method to select an optimized configuration for system reconfiguration.

There is also simulation- and software-based evaluation methods to optimize system configuration. Leng et al. [28] introduced a rapid reconfiguration method which utilizes digital twins. Presented digital twin consists of two parts, the first part being semi-physical simulation model of the system and the second part being optimization model. Data from the semi-physical simulation model is entered into the optimization model, and after the optimization, the results are returned to the semi-physical simulation model for configuration verification. [28] Han et al. [29] presented reconfiguration decision-making system which utilizes Internet of Things technology and sensors for data acquisition from a physical system. Based on to the acquired data from the physical system, decision-making system detects the reconfiguration situation and builds a reconfiguration plan [29]. Renna [30] developed a reconfiguration decision-making method focusing on a simulation environment utilizing game-theory approach (Gale-Shapley method). In this method, underloaded and overloaded systems and machines are coupled for evaluation and the target is to add tasks from the overloaded systems to the underloaded systems to create new configurations. [30] At the Tampere University, Järvenpää, Siltala and Lanz [31, 32] have presented capability matchmaking software which faster production system design and reconfiguration planning.

3. Concept for reconfiguration feasibility analysis

The decision to change configuration of a production system and the choice of a new replacing configuration is very complex because several factors influence to the decision. From an economic perspective, labor and changeover costs are just a few examples of the various cost factors which influence to decision-making. Similarly, available personnel, skills, and

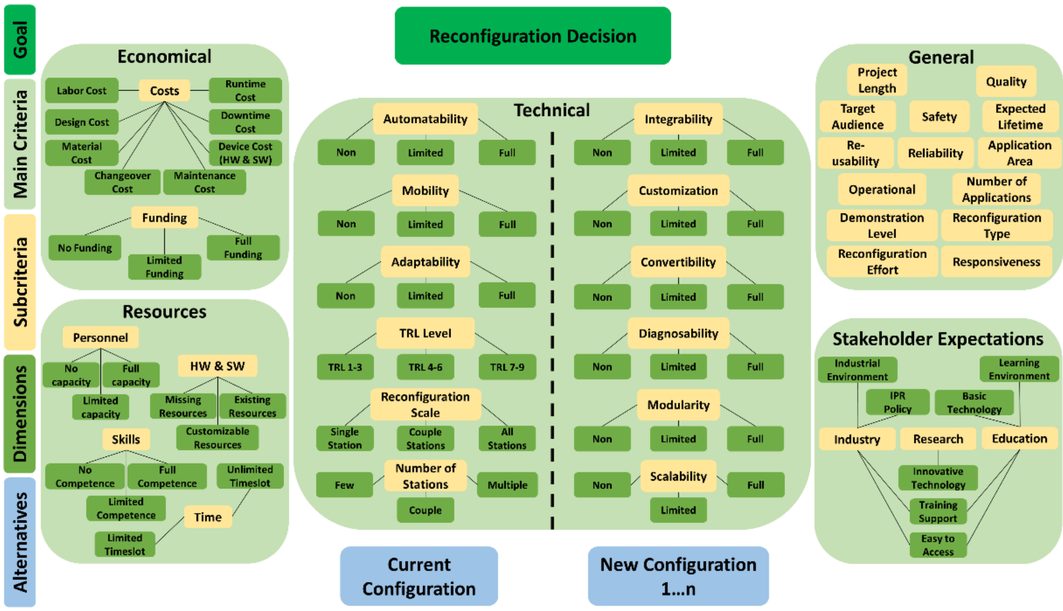

Fig. 1. Dimensions for reconfiguration decision-making.

tools over a certain timeslot are key factors when considering the most appropriate time for reconfiguration. Not to mention all the interests of stakeholders and technical requirements for the system. Several requirements combined with different configuration alternatives in the concept design phase of the reconfiguration planning make it difficult and complicated to determine the configuration to be used in the future. It has been shown that developing a decision-making method to select correct reconfiguration is not easy.

This article proposes a concept for reconfiguration feasibility analysis which is utilized in early-stage reconfiguration planning and decision-making because then is the most opportune moment for erroneous design decisions. The goal is to define whether to reconfigure or not, what is the most appropriate configuration to be used and whether the time is right for reconfiguration. Concept utilizes AHP method to rank potential early-stage configuration alternatives: which of the proposed reconfiguration concepts are feasible and most promising from the technical, resource and economic point of views. The method doesn't give absolute results but supports decision-making when defining the need for reconfiguration and choosing the most appropriate reconfiguration concept. The scope is limited to reconfigurable pilot lines. 'Pilot line is a pre-commercial ('test before invest') production or prototyping environment, physical or virtual that enables learning through experimentation in new product, service and business development' as defined by the Sustainable Industry Ecosystem (SIE) consortium. RPLs will serve both industry and academic community enabling education, research and industrial RDI collaboration between SMEs and researchers.

Proposed feasibility analysis consists of four (4) steps. The first step (1) is to outline preliminary early-stage concepts for reconfiguration. The second step (2) is to recognize and choose the most relevant technical, resource and economical requirements of the pilot line as well as the expectations of stakeholders based on the current and future needs. The third step (3) utilizes AHP method to rank alternative reconfiguration proposals based on the requirement criteria selected in the previous step. In the last fourth step (4), final decision is made using the results from the third step: whether it makes sense to make a configuration change at this stage and what is the most promising reconfiguration concept.

3.1. Step 1: preliminary reconfiguration concepts

New demonstration cases, either from industry or from the academic community, arise on a regular basis to be tested at the RPLs. This leads to a constant need for the reconfiguration evaluation: whether the current system configuration can fulfill the new requirements of the new test cases or not. Simultaneously, the question is whether the configuration change is possible at this point or at all. To answer these questions, the first step is to define preliminary concepts for reconfiguration. At this stage, only the main ideas, expectations and preliminary requirements are collected from stakeholders in order to create preliminary concepts for reconfiguration.

3.2. Step 2: dimensions for reconfiguration decision-making

Once the preliminary reconfiguration concepts have been defined, the next step is to gather all the relevant current and future requirements for reconfiguration. Requirements of RPLs differ from the requirements of traditional RMSs. For example, in production cases, the target is to achieve the desired production capacity for a certain product family. However, the goal of the pilot lines is to serve as many companies as possible with changing test cases. Based on the collected requirements, initial plans for the reconfiguration concepts can be updated.

Fig 1. presents dimensions for the reconfiguration decision-making. Five main categories of criteria have been defined for the reconfiguration decision-making: economical, resource, technical and general requirements, and stakeholder expectations. Each of the main criterion categories has its own subcriteria which dimensions are also visualized in Fig. 1. To reach the goal (reconfiguration decision) various reconfiguration alternatives are presented, including the current configuration of the pilot line. Illustrated requirements are compiled from the literature review (Section 2) and internal expert workshops within the SIE consortium [33]. Presented dimensions are only exemplary requirements and expectations. There are multiple different requirements outside the scope that need to be recognized and considered at this step.

Economical requirements are divided into two main subcriteria: funding and costs. Funding describes the financial condition of the pilot line, whether there is existing, coming, or missing funding. If the funding is limited, it states that additional funding has to be gathered either to extend the lifetime of the current configuration or to implement configuration change. Costs subcriteria includes labor, device, changeover, and runtime costs. Estimated costs of the new configuration and the actual costs of the current configuration can be compared with numerical values.

Resource requirements are divided into four different subcriteria: personnel, skills, time, and hardware (HW) and software (SW). Personnel subcriteria represents the personnel capacity which is available either to maintain the current configuration or to enable configuration changeover. Skills subcriteria specifies is the competence level of the personnel high enough to fulfill the needs of the configuration. Skills can be for example design, assembly, and marketing skills. Time resources determine whether there is enough time to do the configuration change or whether the timeslot for the changeover is appropriate. HW & SW subcriteria determine needed hardware and software for a specific configuration.

Different stakeholders have varying expectations for RPLs. SMEs need industrially relevant test-before-invest environments where access and intellectual property right (IPR) policies are defined. Both SMEs and education need training support when using piloting environments. Education requires basic technologies and research in turn needs innovative technologies. As has been seen, different stakeholders have conflicting expectations which makes reconfiguration planning challenging.

Technical requirements consist of two subcriteria: RMS key characteristics and other technical parameters. RMS key characteristics include the six core principles of RMS: modularity, integrability, convertibility, scalability, customization and diagnosability. Technical parameters are other supporting technical and structural requirements for RPLs, such as mobility, adaptability, and technological readiness level (TRL) of a pilot line. Measuring the dimensions of technical parameters at the concept design phase can be challenging, so the dimensions of the parameters can be described at the general level, for example pilot line can be modular partially, not at all or completely.

General requirements include viewpoints from quality, operation, and safety among other aspects. Operational requirements may include criteria for the number of different applications to be tested on the pilot line. The expected service lifetime (short, medium, long) of the configuration, the application area (products, technologies, processes) and the total reconfiguration effort are one of the other key requirements which should be considered when selecting a suitable reconfiguration concept.

3.3. Step 3: reconfiguration concept ranking

After the requirement specification, AHP methodology is used to define reconfiguration indexes and rank proposed reconfiguration concepts. Methodology uses pairwise comparison of solution alternatives in relation to the selected evaluation criteria and goal. Based on the pairwise comparison, numerical priorities are formed for the evaluation criteria and alternative solutions. Typically, AHP methodology is utilized in selection, prioritization, evaluation, and ranking applications to simplify decision-making on complex issues [34].

The first phase of this method is to select relevant evaluation criteria from the previous step and determine priority values for the used criteria. In this phase, the first step is to create a hierarchical structure with goal (reconfiguration decision) at the top level, selected evaluation criteria (requirements) in the levels 2…n, (where the level 2 is for the main evaluation criteria and levels 3…n are for the sub evaluation criteria) and solution alternatives (preliminary reconfiguration concepts) at the bottom level as shown in Fig 1. The second step in this phase is to do the pairwise comparison of the evaluation criteria. Comparison of different criteria is done by utilizing rational reasoning and intensity of importance scale typically from one (1) to nine (9). Value one (1) defines a situation where both criteria are equal in relation to goal and parent criteria. Respectively, value nine (9) defines a situation where one of the compared criteria is dominant over other criteria. Comparison results are transferred to a pairwise comparison matrix and after the calculations priorities/weightages of the different evaluation criteria are calculated. Priorities can be presented either in the global or local levels. Third step in this phase, if needed, is to calculate a consistency value to check whether the calculated priorities are realistic or not.

Once the priority values have been defined for each evaluation criterion, reconfiguration indexes for reconfiguration concepts are determined, and the concepts are ranked accordingly. At this phase, pairwise comparison of the solution alternatives is made in relation to the goal and evaluation criteria by using the priority values defined in the previous phase for the evaluation criteria. As a result, AHP method determines reconfiguration indexes (priorities) between the different solutions. The highest value ranks first.

3.4. Step 4: evaluation and final decision

The final step is to analyze the result of the AHP method and decide which preliminary reconfiguration concept will be transferred to the detailed design phase if the result is not to use current system configuration. Normally, it’s decided to use the reconfiguration concept with the highest reconfiguration index. However, there might be cases where other factors affect to the decision-making. For example, a reconfiguration concept with the highest reconfiguration index is dominant over other reconfiguration concepts due to its technical and resources properties but there isn’t enough budget to implement it. In this case, other solutions need to be considered. The results of the AHP method are indicative thus the accuracy of the AHP results must be assessed. Therefore, the final reconfiguration decision must always be done after the detailed design.

Fig. 2. HRC Pilot Line at the Tampere University.

4. Case study: reconfigurable pilot line

Human-Robot Collaboration Pilot Line (HRC Pilot Line) presented in Fig. 2 is an example reconfigurable pilot line developed at the Tampere University. HRC Pilot Line serves as a testbed for companies to explore, test and validate potential new product, process, and service solutions that they could transfer into their own production facilities. It offers an opportunity for the SMEs to adopt try-fast-fail-fast design cycle without disturbing daily operations.

The proposed method for the concept phase reconfiguration feasibility analysis is demonstrated in the HRC Pilot Line on a small scale for simplification. The need for reconfiguration is possible as a new research case is planned to be implemented on the pilot line. The first solution alternative is to try to implement it with the current configuration of the system. Another solution alternative is to change the pilot line configuration by adding a linear robot track to the system (Step 1). Overall economical, technical, resource and general requirements as well as the stakeholder expectations form the used evaluation criteria (Step 2). Results of the AHP method are shown in Fig. 3 (Step 3). The first phase is to do the pairwise comparison of the evaluation criteria and determine criteria weights (see the 'Criteria Weights' column in phase 3.4 in Fig 3). In this case, technical criterion has the highest importance (0.37) and the general criterion the lowest importance (0.08). The next phase is to do the pairwise comparison of the reconfiguration alternatives in respect to the evaluation criteria (phase 3.1), transfer the intensity factors to the pairwise comparison matrix (phase 3.2) and then calculate normalized comparison matrix (phase 3.3). The normalized values are then multiplied by the evaluation criteria weights and added together (phases 3.4 and 3.5). Based on the pairwise comparison calculations of the alternative solution candidates, the highest reconfiguration index (0.62) is given for the new configuration in which the robot track is added to the system. The final decision (Step 4) is to move to the detailed design phase with the proposed new configuration because of the reasonable economic factors, moderate availability of the resources, higher stakeholder expectations for achieving new research cases with the new configuration, and the technical superiority in relation to the current old configuration.

5. Discussion & conclusion

This article presented the concept for the reconfigurable pilot line: test-before-invest piloting system which functionality and structure can be changed according to changing needs of industry, research, and education. Dimensions for the reconfiguration decision-making and concept for the early-stage reconfiguration feasibility analysis are presented. Proposed feasibility analysis finds the most promising reconfiguration candidates from technical, resource and economical point of views during the concept design phase. The analysis doesn't provide final results: selected reconfiguration concept is always transferred to the detailed design phase before the final reconfiguration decision.

The complexity of the analysis depends on the number of criteria and alternative solutions used in the decision-making: more criteria and proposed solution candidates, more complex hierarchical model and pairwise comparison matrix. If there are overlapping, inaccurate or missing evaluation criteria, these will affect to the reconfiguration decision. At this stage, there hasn't been set limit values for evaluation criteria. This doesn't facilitate pairwise comparison. Current system configuration also affects to the result: if the current configuration is excellent according to AHP results, it may not be changed without further consideration. Collected system data from previous reconfiguration implementations would facilitate decision-making. Finding valid evaluation criteria, with the right scope and realistic priorities, conflicting expectations of different stakeholders and uncertainty about future needs are still the key challenges for reconfiguration decision-making.

6. Future work

For future work, there are a few development targets. First, universal guidelines for the preliminary configuration concept design must be established. Second, presented dimensions for the reconfiguration decision-making must be evaluated. It should be identified whether the presented requirements are relevant for the reconfigurable pilot lines and whether there are

Phase 3.1 - Pairwise Comparison Table

Solution Alternatives: New Configuration (Option A) & Old Configuration (Option B)

	Solution Alternatives Option A	Option B	More Important Option A or Option B	Intensity (1-9)	Reasoning
Economical	New	Old	B	3	Big investment and higher maintenance costs for the new configuration
Resources	New	Old	B	2	At first, new configuration requires higher changeover and runtime resources
Technical	New	Old	A	4	Technical advantage over the old configuration
Expectations	New	Old	A	5	High expectations for the new configuration to increase the number of research cases
General	New	Old	A	3	Better quality, wider target audience and expected longer service lifetime

Phase 3.2 - Pairwise Comparison Matrix

Economical	New	Old
New	1	1/3
Old	3	1
Sum	**4,00**	**1,33**

Phase 3.3 - Normalized Comparison Matrix

Economical	New	Old	Priority
New	1/4	1/4	**0,25**
Old	3/4	3/4	**0,75**

Phase 3.4 - Unweighted Performance Score

	Criteria Weights	New	Old
Economical	0,15	0,25	0,75
Resources	0,21	0,33	0,67
Technical	0,37	0,80	0,20
Expectations	0,18	0,83	0,17
General	0,08	0,75	0,25
Total	1,00	2,97	2,03

Phase 3.5 - Weighted Performance Score

	New	Old
Economical	0,04	0,11
Resources	0,07	0,14
Technical	0,30	0,07
Expectations	0,15	0,03
General	0,06	0,02
Total	**0,62**	**0,38**

Fig. 3. Reconfiguration index determination for case study.

overlapping, missing or additional requirements and criteria. Also, relations between different requirements and detailed definitions and measurement methods for individual requirements must be determined. Third, specific limit values for individual evaluation criterion need to be defined to facilitate the analysis. Finally, presented concept for the early-stage reconfiguration feasibility analysis has to be validated in full scale.

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