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Integration of Engineering and Manufacturing Change Management: Infrastructure and Scenarios for Teaching and Demonstration

Eldar Shakirov[a,*], Felix J. Brandl[b], Harald Bauer[b], Niklas Kattner[c], Lucia Becerril[c], Clement Fortin[d], Udo Lindemann[c], Gunther Reinhart[b], Ighor Uzhinsky[a]

[a] *Skolkovo Institute of Science and Technology (Skoltech), Center for Design, Manufacturing, and Materials, 121205 Moscow, Russian Federation*
[b] *Technical University of Munich (TUM), Institute for Machine Tools and Industrial Management (iwb), 85748 Garching, Germany*
[c] *Technical University of Munich (TUM), Laboratory for Product Development and Lightweight Design (lpl), 85748 Garching, Germany*
[d] *Skolkovo Institute of Science and Technology (Skoltech), Space Center, 121205 Moscow, Russian Federation*

* Corresponding author. Tel.: +7-495-280-1481; *E-mail address:* eldar.shakirov@skoltech.ru

Abstract

Manufacturing companies nowadays face difficulties due to inefficient change management in domains as engineering, manufacturing, logistics, etc. Even though there are powerful software solutions and process-based methods available, it is uncertain how to efficiently react in an integrated manner to interdisciplinary changes. Whereas learning factories show great results for manufacturing education, change management is still uninvestigated in this context. Therefore, this work presents the basic infrastructure and use case for a demonstration and teaching environment that is currently being developed at Skoltech in collaboration with TUM. The results are derived from an integrated process for engineering and manufacturing change management.

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Keywords: learning factory; engineering change management; manufacturing change management; product lifecycle management; systems engineering; systems architecture

1. Introduction

Twenty-first-century manufacturers are coping with customer's increasing demand for diversity by embracing Mass Customization. This concept was coined in Boston by Davis [1] in 1989, who envisioned this oxymoron to become a significant competitive market advantage for companies [2]. However, due to variants and shorter innovation cycles, Mass Customization leads to a high amount of changes within the product and the manufacturing system. It was mentioned that computer-aided design and manufacturing (CAD/CAM) solutions can reduce machine downtime during changes [1]. However, 30 years later, industry still has not fully adopted an integrated digital support for Mass Customization. Researchers have identified four areas, which would enable Mass Customization: methodologies, processes, manufacturing technologies, and information technologies [2,3]. While some of the research topics have been discussed extensively, an important issue that still has not received sufficient consideration is the integration of engineering and manufacturing change management activities. We have encountered many examples in industry showing that the lack of change synchronization has led to serious failures and budget overruns.

To date, various studies [4 - 7] have described the IT infrastructure required for integrating engineering and manufacturing design processes. Also, researchers have

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developed reference processes for Engineering Change Management (ECM) [8] and for Manufacturing Change Management (MCM) [9] to provide procedural support in these two particular domains. Moreover, Bauer et al. [10] have presented a conceptual structure of a collaborative change management process, which aim is “to minimize coordination effort while fostering an early identification of change effects across the different domains”. The authors of this work suppose, that further study of this issue is critical to help industry develop fundamental organizational capabilities, which are necessary to increase changeability [11], and to achieve the potential of the infrastructures described in previous studies [4]. Companies need to understand the benefits and practical application of the collaborative process. For this purpose, this paper presents 1) the required learning environment for training a collaborative change management process based on [10], and 2) the underlying general methodology for the development of infrastructure and scenarios for process teaching and demonstration.

2. Context

Based on the current state of research in this area, the authors propose, that the further development of an integrated engineering and manufacturing change management reference process is instrumental for companies to advance [10, 12]. The reference process addresses the lack of awareness regarding the direct and indirect change effects during the product creation process – which is one of the root problems. Another problem is the lack of deep understanding for the importance of an integrated approach in academia and industry. It can, thus, be suggested that by recognizing the benefits of and learning how to apply the integrated approach within a teaching scenario, industry will be able to better address the central questions of Mass Customization. Therefore, this study poses the following central research question: “How to demonstrate and teach students and practitioners an integrated change management processes?” Based on this, two sub-questions were formulated: “how to create a process demonstration and teaching environment?” and “what kind of scenarios and infrastructure are required for teaching and demonstrating the integrated change management process?”

3. Methodology

The current research is a result of a collaborative effort between the Skolkovo Institute of Science and Technology (Skoltech) and the Technical University of Munich (TUM), which was established to achieve overlapping objectives. Skoltech is developing a Cyber-Physical Systems laboratory, which has two parts: product development and manufacturing system development. This infrastructure offers a platform for the realistic application of change management reference processes developed in the scope of the SFB 768 project by researchers of TUM [8, 9].

Since the objective of this cooperation is to develop a teaching facility, we decided to adopt the learning factory concept. This concept has already been proven to successfully implement a “learning-by-doing” approach to connect academia and industry [13]. The following presents the necessary steps for the learning factory development based on the procedures for the facility planning [14].

3.1. Analyze Project Stakeholders

Any factory development is associated with investments and expectations by different parties of the project. In order to identify all of them and their interests, the project should be approached systematically. According to the NASA Systems Engineering Handbook [15], the first step is to identify all stakeholders of the system and their expectations. Therefore, one needs to answer the following question: which group or/and individuals are affected by or somehow influences the project’s objectives? For the learning factory development, stakeholders include trainers, participants, visitors, operators, suppliers, and regulators. They define general requirements concerning the learning goals and the learning factory setup.

3.2. Define Learning Goals

A learning factory operates based on predefined scenarios. In this context, a scenario describes a reality-based use case that is simplified in order to address and demonstrate the defined learning goals (i.e. processes, philosophies, methods, tools, etc.). A learning goal is defined by the targeted gain of theoretical knowledge or practical skill. However, to develop the adequate training scenario, a particular product and corresponding manufacturing infrastructure is required.

3.3. Select Product and design Manufacturing Processes

The selection of the product is influenced by the teaching goal and stakeholders’ expectations, what can be expressed through three product properties: 1) *demonstrative* – the designs of product and manufacturing process are conveying the teaching goal; 2) *comprehensible* – the designs of product and manufacturing process are understandable; 3) *feasible* – the designs of product and manufacturing process are economically feasible. This determines the criteria formulation and, hence, helps to choose a proper product. A FRDPARRC table or Pugh chart can be used as a supporting tool [16]. Based on the selected product, a corresponding manufacturing process is designed using Value Stream Mapping (VSM) or the business process network diagram.

3.4. Develop Teaching or Demonstration Scenarios

Having the product and its manufacturing processes specified, the application of the to-be-taught method, tool or process, etc. creates a holistic scenario in the learning factory. Thereby, theoretical knowledge is applied in a simulated scenario inside an industrial setting for teaching or demonstration purposes.

3.5. Derive Infrastructure Requirements

Finally, the learning factory operations, infrastructure, equipment, documents and staff can be detailed. With this, the factory would be ready for testing and iterative improvement. The next section is devoted to the application of this approach for the learning factory design for integrated engineering and manufacturing change management purposes.

4. Developing the learning factory for the specific use case

As mentioned above, one of the core goals of this study is to demonstrate and analyze engineering and manufacturing change management process integration. For this purpose, an existing teaching and demonstration environment at Skoltech needs to be extended. Skoltech has already built a product development (PD) part, demonstrating model-based systems engineering based on a Siemens PLM portfolio [17]. The purpose of this learning factory is to augment the PD laboratory with the manufacturing system in an integrated manner and to close the product design, engineering, and manufacturing loop.

4.1. Stakeholders analysis

a. External Stakeholders

Since the project is aimed to be valuable for Skoltech, industry, academia, and society, the authors identified them as the external stakeholders, i.e. those who influence or are affected by the learning factory. Fig. 1 shows the external Stakeholder Value Network (SVN) map – a model to capture the 2nd order effects and value loops [18] –, which suggests the following principal implications:

1) The product selection should facilitate the minimization of investment required for the learning factory implementation, e.g., to select a product already designed by the PD laboratory;
2) The design and manufacturing processes of the product should represent common industry standards and address research related problems.

These conclusions directly affect the learning factory setting regarding the organizational and technical system development.

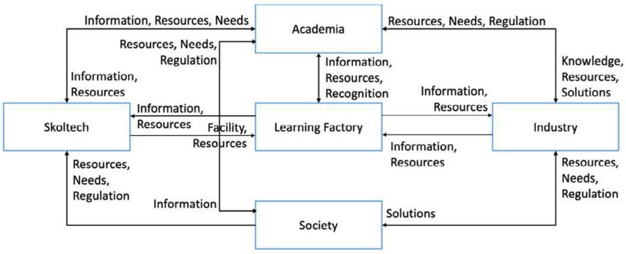

Fig. 1. External SVN map (e.g., *Society* provides Resources, Needs, and Regulations to *Academia*, *Industry*, and *Skoltech*, and receives Information from *Academia* and Solutions from *Industry*).

b. Internal roles

Since the learning factory aims to be an interdisciplinary engineering change showcase serving as a connector between academia and industry, its structure should reflect the main interactors of the product development and manufacturing departments in industry. According to section 3.1, various stakeholders were identified and grouped into main representatives:

Product Development dept. (PD): product design and change management; product requirements management.

Manufacturing Engineering dept. (ME): product design for manufacturability analysis; product manufacturing documentation development; machines, equipment and tooling definition; manufacturing process definition.

System Management dept.: learning factory management in line with the vision of the project; development and update of system architecture, data structure, change management policy.

Inspection & Testing dept.: inspection and testing of the product, processes and the manufacturing system; commissioning; tests' reports generation; verification and validation of the product, processes, and resources.

Logistics dept.: communication with suppliers; design of inbound and outbound material flows, schedules; production planning activities support; contracts management.

Manufacturing System Operating dept.: manufacturing system planning, control, and operation; manufacturing processes feasibility analysis.

Suppliers: supply components and resources (e.g., assembly components, energy, water, tooling, compressed air, software, etc.); contracts management.

Customer: product requirements formulation; product usage; contract management.

Sales and Marketing dept. (SM): market analysis and cost definition; communication with the *Customer*; contract management.

4.2. Learning goals

In this learning factory, a systematic management approach to integrated engineering and manufacturing changes, based on academic reference process models, are planned to be taught and demonstrated to students and industry participants. These processes were developed by TUM research groups based on an extensive literature review, several expert interviews, online surveys and industry case studies in the collaborative research group (SFB 768) [8,9].

By depicting the processes and corresponding roles on the same plot, an integrated reference process can be developed as shown in Fig. 2.

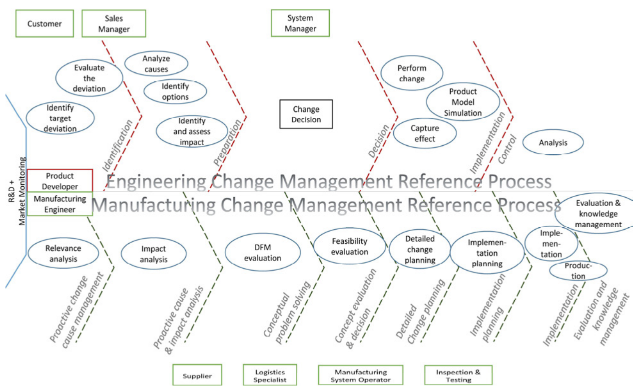

Fig. 2. Plot draft for processes integration.

4.3. Product selection and manufacturing process design

According to 3.3, the following product selection criteria were aggregated and prioritized based on the colligated implications.

Criteria 1 – to close the loop of product development and production, the product should be or assumed to be developed by the PD department of the learning factory (*demonstrative product*).

Criteria 2 – the product should have a reasonable complexity, i.e., the product should include an appropriate number of parts (e.g. 10-20) of a moderate machining and assembly complexity; to be both representative for industry and applicable for educational purposes (*demonstrative and comprehensible product*).

Criteria 3 – the product should be customizable to address Mass Customization and therefore include complex change management issues (*demonstrative product*).

Criteria 4 – the product's parts should be producible by standard CNC industrial machines (*feasible product*).

Criteria 5 – the product should be made of reasonable materials, which are fast to machine and cheap to buy (*feasible product*).

The first criteria restricts the selection to two products already developed in the PD laboratory of Skoltech: the deployable unmanned aerial vehicle (UAV) and the high-altitude pseudo satellite (HAPS). Since both are of a relatively high-level complexity (100+ parts) for teaching purposes, the product selection moves to the subassembly level. Most of the HAPS parts fail on fourth criteria because of the oversize. Exploring criteria three and four, the only relevant option that remains is the UAV propulsion subsystem. It consists of 15 metal and plastic parts that fulfill the targeted complexity and size criteria as shown in Fig. 3.

The manufacturing operations were analyzed using the value stream mapping model and then used for the infrastructure requirements definition.

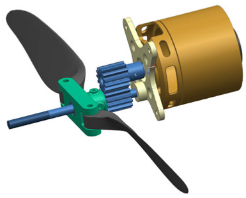

Fig. 3. UAV propulsion system 3D model

4.4. Demonstration scenario

Realistic and industry-related use cases are necessary in order to demonstrate the added value of a standardized reference process for the management of changes. We developed two use cases for the demonstration of change propagation: customer requirements change and manufacturing technology change. In this work, the synthesized steps of the first use case, the customer requirements change, are presented. Fig. 4 shows the final state of an animation, which illustrates the change propagation step by step, linking the basic process phases in the reference model, based on the standardized model (cf. Fig. 2). To underline the importance of interdisciplinary decision making, the scenarios use Quality Gates, represented by a traffic light with a set of specific requirements. In order to pass the gate, it is necessary to meet the set requirements [19]. The steps of the first use case are described below.

1) PD and ME teams proactively investigate potential change causes: R&D as an internal search scope for the company, and market analysis as an external.
2) Customer wants to change the product (e.g. increase the payload of the UAV).
3) PD and ME identify target deviation in the design and analyze the relevance for changes in manufacturing.
4) SM and PD departments collaboratively create the product design change request, following customer needs.
5) PD evaluates the deviation and analyze the product design change propagation.
6) If the design change is necessary, then PD analyzes root causes that made Customer want to change the requirement.
7) PD identifies options to solve the problem (e.g. aircraft aerodynamic scheme change, materials change, design change).
8) PD develops engineering change concepts (ECCs), based on the chosen options.
9) The impact of design change concepts realization is analyzed from PD and ME perspectives; concepts are further developed through the loop of steps 3-9.
10) Based on the previous analysis, the concept is selected.
11) To pass the Quality Gate and proceed, PD and ME must agree on the preliminary manufacturing feasibility of the concept.
12) The manufacturing change request (MCR) is formulated.
13) ME analyze the developed ECC Design for manufacturability (DfM).
14) Agreement on feasibility opens the gate to PD change decision. Disagreement returns the process to step 9.
15) The opening of the gate allows PD to make the design change decision.
16) PD performs the detailed product design change, its simulation, and analysis.
17) ME evaluates the developed design and develops manufacturing change concepts (MCCs).
18) The MCCs must fulfill formal requirements established by the company, represented by the warning Quality Gate.
19) ME, supported by other stakeholders input, conducts the manufacturing feasibility evaluation of the developed MCCs.
20) For ME to carry out the detailed design and implementation of the manufacturing change, PD and ME must come to a collaborative decision on the product design change, to avoid future extemporaneous and costly changes in the manufacturing change implementation. This decision is based on the requirements fulfillment of one of the most critical Quality Gates with three checkpoints:
    a. Change and change propagation analysis is done.
    b. Stakeholder review is done.
    c. Decision confirmations from other stakeholders are received.

21) The decision would either let ME and supporting stakeholder proceed to next steps or return PD and ME to product design, step 15.
22) With the detailed design the manufacturing change order (MCO) is released.
23) The MCO triggers the implementation planning (with the support from other stakeholders).
24) During the MCO implementation the production is ramping-up. The Quality Gate does not allow to approve the manufacturing engineering deliverables until the production runs stable in the changed configuration. In this phase potential change propagations and further change details are handled through backwards connections and close collaboration between PD and ME.
25) Once the gate is open, “lessons learned” are documented.
26) Stakeholders analyze the lessons and improve their operation for further cycles.

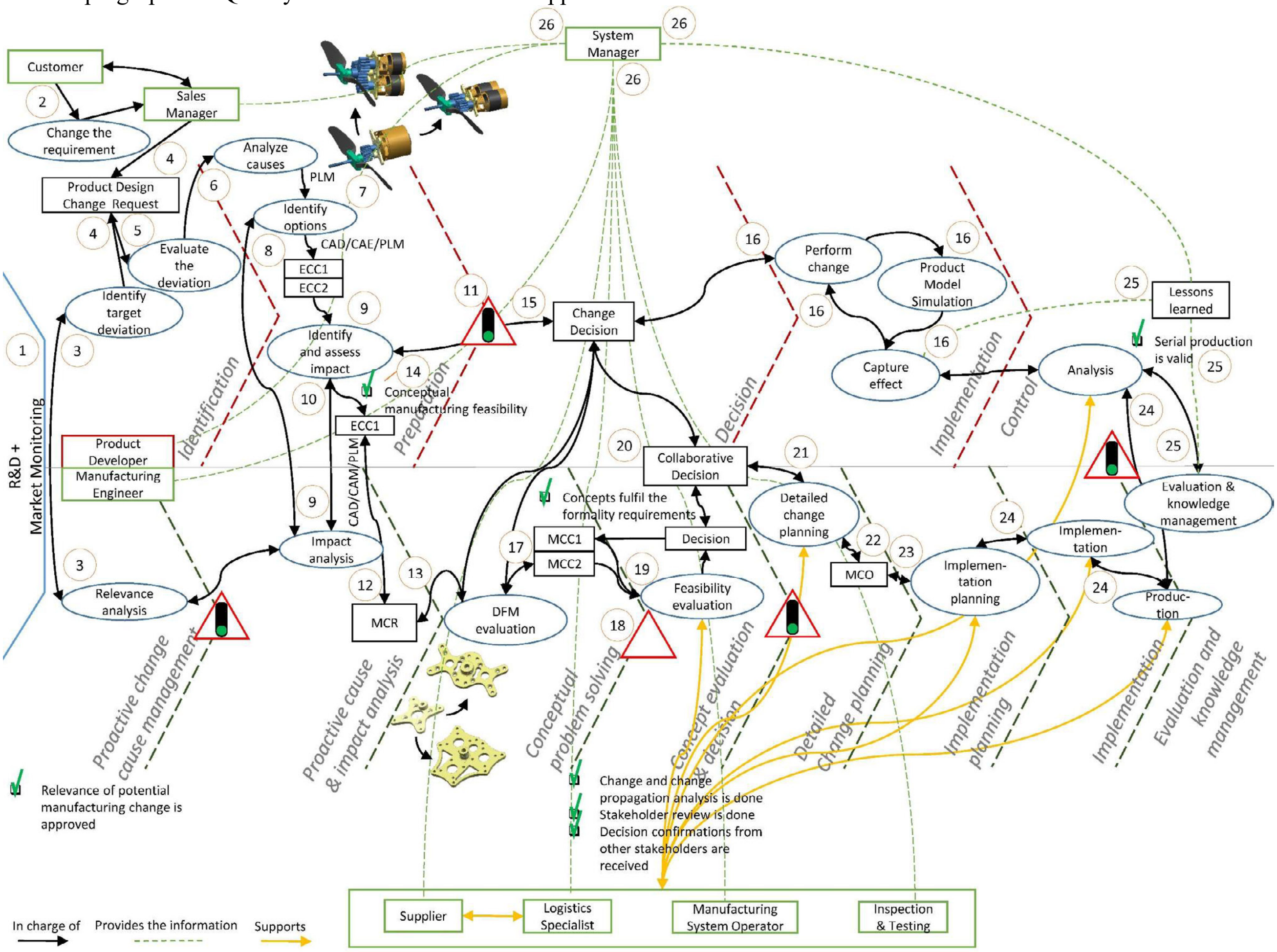

Fig. 4. Customer requirements change use case visualization (an animated version is available for download at tiny.cc/ECMMCM).

4.5. Further steps within the learning factory development

Once the scenarios have been developed and the infrastructure described, the layout can be designed. For Skoltech, the next steps are the procurement of the equipment and software, and the implementation of the layout and scenarios on the greenfield.

4.6. Infrastructure requirements

Based on the description of the integrated engineering and manufacturing change management scenario (cf. 4.4) and the value stream model (cf. 4.3), the infrastructure and equipment for the learning factory can be derived.

Table 1 shows the list of necessary hardware, software, and other prerequisite equipment, synthesized according to main components of a manufacturing facility by [20].

5. Conclusion

As mentioned in section 1, the project underlying this paper aims to demonstrate and teach integrated engineering and manufacturing change management to practitioners and students. The overall goal is to increase the attention from academia and industry towards this topic. Answering the research questions (see section 2), this work has derived the following: (1) the learning factory concept presents a promising way to demonstrate and teach students and practitioners the integrated change management processes.

Following the five steps described in 3.1 – 3.5, a training environment can be designed. (2) Concerning the collaborative change management, teaching scenarios can be created by starting with different change causes and following the reference process. The scenarios require an integrated product design, engineering, and manufacturing infrastructure, consisting of hardware and software equipment (cf. Table 1).

Table 1. Learning factory infrastructure requirements.

Required Equipment	Required Software solutions
Milling machine tool with CNC	Product Lifecycle Management
Turning machine tool with CNC	CNC controllers
Sawing machine tool	Discrete-Event Simulation (DES)
Measuring, finishing, and assembly equipment	Computer Aided Design, Engineering and Manufacturing (CAD, CAE, CAM)
Internet of Things (IoT) equipment	IoT platform
Processes automation equipment	Predictive analytics platform
Testing and models validation equipment	Manufacturing Execution System (MES)
Hardware-in-the-Loop (HiL) testing equipment	Advanced Planning and Scheduling (APS)
Transportation equipment	Virtual commissioning
Additive manufacturing equipment	Enterprise Resource Planning
Classroom equipment	Warehouse management system

By following a given reference process and concrete change scenarios within an industrial setting, academia and industry professionals can learn how to effectively respond to changes. One key lesson of the teaching and demonstration scenarios would be that a small change is never a small change: it triggers a chain of associated connections, which can lead to big failures if not controlled properly.

Further research can explore teaching and demonstration of other associated questions of integrated change management. These are examples of relevant topics: the data structure necessary to support the efficient integration of the change procedures; challenges of new technology's introduction (e.g., Additive Manufacturing) that the integrated change management process needs to address; the integration of software solutions for infrastructure deployment facilitation; the education practices for interdisciplinary skills development.

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