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Procedia CIRP 88 (2020) 15–18

www.elsevier.com/locate/procedia

13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, CIRP ICME '19

System dynamics modelling and learning factories for manufacturing systems education

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Abstract

Manufacturing systems are complex socio-technical systems with non-linearities, accumulation, flows and delays that challenge decision-making processes. System Dynamics (SD) is a valuable approach to analyse and understand complex interlinkages. This paper discusses how SD can be applied to learning factories (LF) at manufacturing education for enhanced learning outcome. LF are physical, full scale high-fidelity simulators for manufacturing education, where students act as operators and train on interaction with humans, machines, software and technology. Using simulations both virtual and full-scale add value in learning outcomes. By using SD, learners can play "what-if" analysis to understand the effects of their decisions.

Peer review under the responsibility of the scientific committee of the 13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 17-19 July 2019, Gulf of Naples, Italy.

Keywords: Learning factory; Interactive learning environments; System dynamics; Smart factory; Manufacturing education; Learning simulations

1. Introduction

The introduction of intelligent computational elements such as sensors, actuators, and Information and Communication Technology (ICT) in production systems have made manufacturing systems smarter but also more complex with interconnected, automated information and material flows. Some call this "Cyber-Physical Manufacturing Systems" as a mix of physical machines, and tools, humans and computer (cyber) systems [1]. The workforce interacting with such complex systems requires more advanced levels of analysis, abstraction, innovation and system thinking [2], and future engineers need to gain both theoretical knowledge and practical skills to master future manufacturing systems. The classic way to give students practical skills is through internship or practice in industry. Due to the complexity and automation levels of the emerging manufacturing systems, this becomes more and more challenging, and the universities needs to create novel learning environments and methodologies to cover this need. A growing number of universities are thus including Learning Factories (LF) as education facilities for training and learning for smart factory ecosystems. However, there are some limitations of LF in education and training, such as limited resources, mapping ability, scalability, mobility and effectiveness [3]. Furthermore is any LF a very limited simulation of an actual manufacturing system, and is lacking the connection to the rest of the manufacturing company. This paper proposes a methodology that uses System Dynamics modelling (SD) and Interactive Learning Environments (ILE) to cope with the these limitations, and allow the students to do both real-life simulation of a cyber physical manufacturing system on shop floor level, but also link this into a simulated manufacturing company where decisions, actions and events on the shop floor will affect the rest of the company and vice versa.

1.1. Learning Factories

To meet manufacturing industries' demand for knowledge and innovations in the age of Industry 4.0, Learning Factories (LF) are established in many educational and industry organisations [4-6] "*The main goals of learning factories are either technological and/or organizational innovation (if*

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Peer review under the responsibility of the scientific committee of the 13th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 17-19 July 2019, Gulf of Naples, Italy.
10.1016/j.procir.2020.05.003

used for research), or an effective competency development (if used for education and training) [4]. There are variations of definitions of what a Learning Factory is, and Abel et al. [4] has developed a morphology for classifying different types of learning factories. The authors of this paper define LF as high-fidelity real-life simulators containing software, tools and equipment used for training, education and/or research. The interaction between humans and human and machines as a socio-technical system is an important aspect. The LF facilities can be used to simulate different type of scenarios to accommodate the learning of the students. This can be learning to collaborate in teams, perform practical exercises applying theoretical knowledge, problem solving, systematic process analysis, maintenance, product design for Industry 4.0 etc.

Tisch and Metternich [3] identifies, however, a set of limitations of LF and among them is the lacking mapping abilities. Mapping ability limitations refers to the fact that LF addresses only the shop floor level and is not capable of addressing the connection to processes at plant and network level. Other important factors highlighted by Tisch and Metternich are the inability of capturing feedback loops with long delays, such as product development, and supplier development. In this paper we suggest a method for connecting a LF with System Dynamics modelling to meet these shortcomings of the LF.

1.2. System Dynamics and Interactive Learning Environments

With a System Dynamics (SD) modeling approach, students learn by building simulation models and/or by using simulation models created by others with interfaces adapted for learning [7]. Simulations in the form of Interactive Learning Environments (ILE) are considered a form of experiential learning, also known as microworlds or "*management flight simulators*" with the aim of learning the structure and behavior of the complex dynamics within an organization [8].

According to Qudrat-Ullah [9], ILEs should have three main components: (i) a computer simulation model to adequately represent the domain or issue on hand with which the decision makers can experience and induce real world-like responses (ii) a user interface capable of allowing the decision makers to make decisions and access the feedback on interactive basis, and (iii) a human facilitator or a coach responsible for conducting briefing and debriefing sessions. ILE are particularly good when targeting complex dynamic decision making that involves multiples decisions, feedback process, non-linearities and time delays [9]. The reason for this is the primary premise of SD which is: the structure of the system drives its behavior [10], in other words it allows the visualization of the different elements of the system and how they interact (structure) and the (behavior). Understanding relationships between structure and behavior allows a better discernment of the system, the problem and improves decision making [11].

2. Experiences from LF simulations

NTNU has 15 years of experience with real life simulation from our hospital simulation centre containing 10 hospital beds with advanced artificial "patients"[12, 13], and an external control centre where the artificial "patients'" symptoms and reactions to treatment are controlled. Furthermore, we have an ambulance simulator and pre-hospital simulation facilities including a car wreck for simulation of in-the-field first aid[14]. For manufacturing simulation, we have two LFs; one simple LF with a manual roller ski assembly line [15] and a "Lean Lab" LF where the product is a simplified and downscaled house. Both these LFs are focusing on teaching lean principles including balancing (Heijunka) and work process analysis and standardisation (Kaizen)[16].

Each of these are used for simulating actual real-life cases using different sets of scenarios given by the teachers.

According to our experience we can extract some common advices on how to run these simulations:

1. In a simulation there are three roles; The teachers, the controller(s) and the simulants/students.
   - The controller(s) controls the scenarios and are supervising data collection and measurements, video recording and technical equipment.
   - The researcher and/or teachers are in charge of the design of the simulation scenario, briefing and debriefing the simulants as well as analysis of the results.
   - The simulants are the "process operators" in the simulation
2. Everybody involved needs a training in the "art of simulation"
3. Briefing of the simulants/students before each run, what is going to happen, step by step
4. Proper debriefing after each simulation run

It is usually not a good idea to surprise the simulants because of the uncertainty and deviations it can create. Unprepared, the simulation will be less realistic, and it could mean a waste of time. The debriefing is the most important part both for learning outcome and research results, giving the opportunity to critically reflect on their simulation; the "*..debriefing phase is important for creating awareness and knowledge in the learners themselves about their own learning, learning process and knowledge creation"[17]*

Fig. 1. Lean lab - a full scale simulator

2.1. Steps of a LF simulation

Here we focus in more classical approaches that tend to be more instructional than problem-based simulation scenarios[18]. The following list shows the typical steps in a simulation[12];

- Design LF simulation scenario(s) and narrative(s)
- Technical preparation of LF for simulation run(s)
- Pre-briefing of simulants
- LF Simulation run(s) with recording of data, videos etc.
- Intermittent analysis of the LF data and results
- Re-run from step 2, 3 or 4 (if necessary)
- Debriefing of simulants including results processing and analysis

The debriefing-phase is especially important, as much of the learning and reflection upon the learning activities are created here. This could e.g. be set up as a reflection seminar with discussions of the learning outcome as well as including analysis of numerical values from sensors, tracking/monitoring data. Questions asked could be e.g.; Could we reach more insight after these simulations? What needs to be changed in the next simulations? Evaluation tools can also be applied in this process of identifying areas where to improve practice and optimize learning[17].

3. Integration of System Dynamics-modelling and Learning Factories

The ecosystem that creates a manufacturing company incorporates other processes than the shop floor manufacturing, such as; logistics, sales, human resources management and product development. Furthermore, will the company be affected by customer requirements, market shares, environmental impact, resource cost and quality, employers and suppliers' knowledge base, etc. Several casual loops can be identified, for instance increased productivity will lead to less cost, increased capacity and (potentially) increased production yield, which can increase sales (given there are enough customer demands), and thus increased profit. More profit can be re-invested in equipment, innovations, research and development to further increase productivity and sales. Increased production yield creates on the other hand typically more energy and materials consumption, and increased waste which needs to be properly managed. Another reinforcing feedback loop is if the quality of the products is not accepted by the customers, sales could decrease reducing the amount of new orders, increased costs from scrap production and handling of customer rejections will decrease the profit. System dynamics (SD) modelling is a tool useful for modelling these casual loops, and the authors have developed an S- model and an Integrated Learning Environment (ILE) to assist the beforementioned LFs.

Even though learning factories have the potential to enable effective, practical experiential learning defined as a high fidelity manufacturing simulation [3], it is mainly constrained to the shop floor. The SD/ILE could expand the learning environment by recreating it in a virtual world with other elements of the complex manufacturing system. This will aid the students to develop a more holistic, abstract and systemic understanding of a simulated "manufacturing company", where the LF can represent a physical simulation of the shop floor, and the SD-model is a virtual model of the rest of the company. By using this duality, the effects that manufacturing has on the other elements of the company and vice versa can be studied in addition to the manufacturing processes. For instance, how will a delay in delivery from suppliers or the amount of incoming orders affect the manufacturing processes? Similarly, how will the profit be affected by delays in production due to technical problems? The proposed methodology uses the LF and SD/ILE as integrated complementary tools in the controlled environments of the learning processes.

Based on the insight described in chapter 2, we propose the following improvement to the LF simulation runs.

- Design simulation scenarios, simulation narrative.
- Technical preparation of LF + If necessary, adjust/rebuild the SD-model.
- Briefing of simulants
- Simulation run(s) with recording of data, videos etc.
- Data exchange between LF and SD-model.
- Intermittent analysis of LF results and implications on the SD-model using the ILE
- Re-run from step 2, 3 or 4 (if necessary)
- Debriefing of simulants, reflection of learning outcome, results processing and analysis using the SD/ILE

3.1. Steps of an integrated SD/ILE- LF simulation

Combined with selected learning outcomes for the LF, the SD/ILE provides a simulation and mapping situation of the effects and interaction with the rest of the system outside the shop floor. The data collected in the LF simulations are exchanged with the SD model. It will provide a tool to gain a more holistic and systemic perspective and increase the students' knowledge of the synergies and complexities of manufacturing in the long run. The students will have a larger scope of opportunities to increase their understanding of the challenges in decision-making - based on more or less reliable data, information and facts(?) given by the cyber physical manufacturing system.

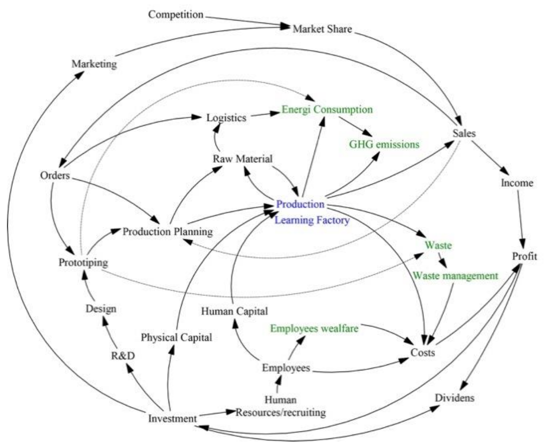

Fig. 2. Casual loop diagram for the LF manufacturing company.

4. Conclusions and Further work

This paper proposes a novel methodology for enhancing the learning outcomes from learning factories (LFs) by integrating the LF with a System Dynamics (SD) model and an integrated learning environment (ILE). The LF is a high-fidelity real-life simulation of the shop floor, and the SD-model is a virtual system dynamics model used for simulating other important aspects of a manufacturing company, including complex casual loops. An iterative learning process using the combination of these simulation tools and the ILE for analysis and reflection was proposed. Further work is needed to create pilots in educational institutions and to validate the proposed methodology and suggest improvements. The authors plan to extend the SD-model to incorporate circular manufacturing concepts to include the dynamics and challenges of the effects of the circularity of products (recycling, remanufacturing and reuse)[19]. The authors also wish to extend these ideas to the “teaching factory” paradigm [20] where a real factory in a real manufacturing company act as teaching aids. Here an SD- model of the real factory and the ILE (and perhaps the LF) can be used to form a “digital twin” for enhanced understanding among the students.

Acknowledgements

This paper was based on activities within SFI Manufacturing in Norway and is partially funded by the Research Council of Norway under contract number 237900. The authors wish to thank the Research Council for funding and the companies participating in the discussions for this paper.

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