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A Case of Demonstrating Digital Factory Potentials through a Modular Approach

Anwendungs-Demonstration von Potenzialen der Digitalen Fabrik mit einem modularen Ansatz

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Abstract: The digital factory concept still needs practical application examples to demonstrate and scale-up its potential benefits. This work presents a pilot project of factory digitalisation that aims to demonstrate the simulation usage in specific projects and daily management practices. A modular approach to discrete-event simulation modelling, project execution and architectural IT framework has been implemented. The architecture consists of a detailed discrete-event simulation model that can be used for virtual commissioning and connected to a performance dashboard. A shared database enables the link with a strategic simulation model and manufacturing system data. The overall approach to the project and outcomes of demonstration activities preliminarily support the following digitalisation hypotheses: a) simulation can be successfully utilised by non-expert end-users; b) multiple performance dimensions can be more easily and quickly analysed and related; c) simulation can be used by industry domain experts and managers to support specific projects and day-to-day management decisions.

1 Introduction

The overarching concept of the digital factory or virtual enterprise (Møller et al. 2008) has been around since the early days of Computer Integrated Manufacturing (CIM). However, the reality has shown than many of the proposed benefits have been difficult to realise. Lessons learned from the CIM crisis include, e.g., the need for complexity reduction by using modularisation and lean technologies, decentralised hierarchies, standardisation, human-centred solutions (Zuehlke 2010). Additionally, problem fields for the digital factory implementation (identified a decade ago) included technical and organisational issues such as networking, maintenance and management of versions, data and knowledge, organisation of companies for efficient design processes across multiple departments as well as commitment

towards the involvement of and cooperation with suppliers including small and medium-sized partners (Bracht and Masurat 2005).

Simulation is an integral part of the digital factory concept (IMAGINE 2013; Azevedo and Almeida 2011; Zuehlke 2010; Kühn 2006; Bracht and Masurat 2005).

Two sets of simulation challenges are addressed in this paper: (i) simulation within the broad scope of digital factory applications, and (ii) development of simulation projects and day-to-day simulation usage. The digital factory concept and the "Industrie 4.0" paradigm are considered.

Concerning the first set of simulation challenges, the concept of digital factory includes the simulation of all the activities during the lifecycle of a factory by means of networked digital models, methodologies and applications to integrate design and planning of manufacturing facilities and processes (Azevedo and Almeida 2011). Additionally, it supports the implementation, control and continuous improvement of plant processes and resources (IMAGINE 2013). Recommendations at EU level are to improve accuracy, reliability, performance, scalability and functionalities of simulation and optimisation tools within the context of digital factories which should foster, for example, the development of modular, flexible and highly adaptable solutions, more efficient/reliable design and re-design, shorter time to production (IMAGINE 2013). Even though significant advances have been recently realised in terms of simulation user-friendliness and data management, further R&D and innovations are needed, e. g., for concretely exploiting the connection with physical systems (re-)design, planning and commissioning in industrial applications. This work is based on a discrete-event simulation environment which strongly relies on modularity of simulation objects, control logics and data management in order to (i) facilitate the building, (re-)usability and maintenance of simulation modules in systems (re-)planning, and (ii) enable the connection with Programmable Logic Controllers (PLCs) for the implementation of virtual commissioning in which virtual prototypes simultaneously support the commissioning of control software, fabrication and assembly of a production system (Reinhart and Wunsch 2007). This approach is in line with four of the envisioned design principles of the Industrie 4.0 paradigm in terms of modularity, virtualisation, real-time capability and interoperability (Hermann et al. 2015). Moreover, simulation tools should access data from actual systems, feed and possibly interoperate with advanced analytics tools for strategic alignment and concurrent measurement and prediction of multiple metrics. The latter aspect is addressed in this work by using a modular architecture to link actual data from the manufacturing system, simulation models, as well as advanced analytics and customised visualisations tools.

Concerning the second set of challenges, future models, methods and tools for the digital factory should address not only technological challenges and technical features but also organisational and engineering knowledge aspects (Azevedo and Almeida 2011; Bracht and Masurat 2005). This embraces the approaches by which simulation projects are developed. The theoretical background here includes conventional step-based approaches for discrete-event simulation studies/projects (Banks et al. 2010; Law 2009). Moreover, Johansson (2006) presented a novel methodology for modular discrete-event simulation of manufacturing systems. We build upon the Johansson's approach to contribute to simulation project developments compliant with the future needs of the digital factory concept and Industrie 4.0 paradigm by

using a five-stage approach presented in Section 4. In the Johansson's methodology, the simulation models consist of standard or special purpose modules (e.g., machines, material handling equipment) that are pre-constructed, verified, validated and maintained by simulation experts while embodying their engineering knowledge in terms of logics, data, interface and graphics (knowledge externalisation). Simulation users (e.g., domain experts such as system technicians or production engineers) then (re-)utilise the same modules with the possibility to change and set only a limited number of parameters in order to (re-)build models and add new perspectives, thus realising knowledge internalisation (Johansson 2006). So doing, the project development lead-times can be significantly reduced (Johansson 2006). Such approaches open space for wider studies of existing or not yet existing manufacturing systems potentially with a stronger engagement of stakeholders (managers without specific knowledge and skills), less misunderstanding risks or data analysis/collection issues with respect to conventional simulation projects carried out end-to-end by simulation experts (Johansson 2006).

We try to extend the Johansson's approach by exploring: a) the simulation usage also by domain experts not necessarily skilled on simulation, b) a wide scope of decisions that can be addressed; c) usage contexts of simulation in industrial practices. Our study demonstrates the benefits of large-scale digitalisation and modelling of an entire factory. The proposed approach aims to streamline and facilitate data gathering, modelling processes, simulation model (re-)use and maintenance. It also contributes to overcome potential difficulties related to stakeholder engagement and data management as well as level of detail required by discrete event simulation (Jahangirian et al. 2010).

The hypotheses and the detailed digital model are presented in Section 2 and 3, respectively. Section 4 includes the application, architectural aspects and related discussion. The work contribution is summarised in Section 5. Conclusions and outlook follow in the final section.

2 Digitalisation Hypotheses

We formulate the following hypotheses that appear to be plausible according to the first interviews and discussions with the stakeholders as well as preliminary indications:

1. *Simulation models can be built and used by professionals not necessarily skilled on simulation modelling*. In our approach there is a division of labour and roles between simulation experts and two types of end-users: domain experts (e.g., industrial engineers working in the manufacturing system) and managers (higher-level decision makers for investment or re-engineering decisions). Domain experts combine pre-built simulation modules, partially set a limited number of parameters, and evaluate the results on multiple Key Performance Indicators (KPIs) dashboards with managers.
2. *Modular simulation models developed with the proposed approach can simultaneously answer questions based on standard and highly customised KPIs at multiple decision levels*. The approach followed focuses on KPIs and charts interrelating multiple metrics in articulated dashboards with focus, e.g., on sizing and performance of material handling systems, capacity utilisation of manufacturing equipment, production and service rates of machines and

handling systems, as well as demand scenarios. Nevertheless, higher level decision-making is supported as explained in Section 4.

3. *Modular simulation models developed with the proposed approach can benefit domain experts and managers for daily management practices as well as strategic decisions*. Simulation models can be traditionally used within the context of an investment or re-engineering project in order to assess and justify the related cost. Even though this conventional usage is also supported in this application, the proposed overall approach aims to build libraries of modules that can be (re-)combined in living models for the management of operations in daily practices.

These hypotheses have been guiding the engagement throughout the project and have been the assumptions on which the digital model has been made.

3 The Digital Model

The digital model reproduces the following system. The system transports empty and full totes in four sizes between a production area and a tote handling areas with buffers, robot handling, tote washing and conveyor transport to a mini-load storage system and dispatch area.

The production area consists of 12 moulding modules each of up to 64 moulding machines, served by 3-5 Automated Guided Vehicles (AVGs) for tote transport between each moulding machine and tote loading/unloading stations, connected to a decentralised tote buffer.

The backbone is a shuttle transport system of almost 1000 meters with approximately 70 shuttle vehicles, transporting totes between the moulding modules and the tote handling area.

Discrete event simulations are normally performed by highly trained simulation experts, and the simulation models are built in specialised simulation software requiring property programming skills.

By structuring the tasks and the model in a new way, the workload can be divided across multiple professionals (Johannsson 2006), and the models can be prepared for future usage such as virtual commissioning.

The simulation model and modelling process are divided into the following main work packages:

1. Material handling objects in a 3D model for discrete event simulation;
2. Flow controllers for applying the overall material flow logics;
3. Input files for generating events such as tote flow, flow rates, order release, breakdown, etc.;
4. Statistics module for monitoring the system characteristics such as performance, utilisation of equipment, buffering, queuing – All relevant statistics are logged in database and files for analysis.

Applying this alternative structure opens for involving the domain experts (system technicians) and managers (system owners) more actively in the modelling process as well as the use and maintenance of the model – an important driver for ensuring the modelling process to reach into the future and towards virtual manufacturing.

The model elements are structured for fast model building and modification by non-simulation experts, building the model by dedicated base objects and in accordance to layout drawing and system documentation by means of pick'n'place. No specific simulation skills are required for model building, but the ability to understand layout drawing and use a 3D modelling environment are the main skills required. Knowledge and insight in the systems functions, operation, controls logics, etc. are important for firstly model verification and adjustment, and secondly model modification, maintenance, and specification of future developments.

The base objects, a total of 14 objects, are developed by skilled object oriented software developers in accordance to specifications and few defined parameters important for preparing the objects for pick'n'place model building and simulation. This includes embedding basic controls logics and functions as well as opening for few relevant parameters settings. A base structure for, e.g., conveyors, AGVs, shuttles, robots and a strong API for simulation features and 3D modelling reduces the development process of the objects. The system flow controller is programmed in C# and successively enhanced for accommodating base simulation runs for this particular system and its characteristics. This also includes logging statistics and event into the repository. Input files for generating events, flow traffic are retrieved from production statistics by the IT department and modified for applying future production scenarios. A screenshot of this detailed discrete-event simulation model created in Experior (Xcelgo A/S) is presented in Figure 1.

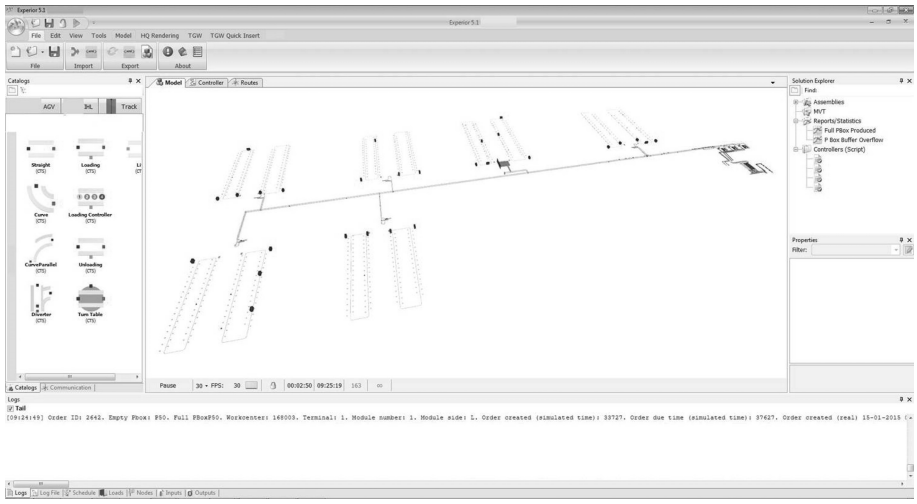

Figure 1: *Overview of a simulation model in Experior (Xcelgo A/S).*

4 Project Development, Applications and Evaluation

4.1 Project Development

The project development follows an approach which aims to streamline model building, (re-)use and maintenance.

By dividing the tasks into work packages and assign technicians with the right competences, the workload is divided across multiple professionals. The necessary simulation competences are applied to the project by assigning experienced simulation experts to the project group. Specific tasks related to simulation are handled by the simulation experts such as validating the input data, preparing scenario input, defining statistics and especially defining setting for simulation runs. This includes arranging simulation workshop and crash-classes in simulation theory for training the users (i.e., the domain experts and managers) in simulation basics.

The entire digitalisation demonstrator project has been carried out as a pilot over the course of less than one year, and encompassing the following stages.

- *Stage 1: Management buy-in and scoping*. The initial interviews and discussions between simulation experts and users take place while defining goals and scoping the system modelling.
- *Stage 2: Establishing the foundation and building the model*. The core aspects of the model (system components, input data, KPIs, etc.) and of the model usage are established. The simulation experts build and validate the modules of the model.
- *Stage 3: Creating applications of the model*. The domain experts, initially supported by the simulation experts, finalise data gathering and create the applications.
- *State 4: Formulating and quantifying the benefits*. Results and insights are analysed and discussed at two levels: (i) domain experts and simulation experts for the sake of validation and further experiments of the users, and (ii) domain experts and managers.
- *Stage 5: Communicating and extending use*. The results and indications for future usage in daily practices are shared among the stakeholders (domain experts and managers).

The aim of the project is to take this first detailed model as a platform for extending the ideas into the entire factory. So doing, the knowledge of simulation experts can be scaled-up and internalised at end-user level for the finalisation of this first digital factory simulation modelling, its usage in daily practices as well as in new simulation projects for manufacturing system modifications.

4.2 Architecture, Preliminary Results and Evaluation

The detailed digital model presented above has been framed in a wider modular architecture consisting of a KPI dashboard for advanced analytics and a strategic discrete-event simulation model built in Simio (Simio LLC). The dashboard is an analytics module which has a business intelligence function to connect the manufacturing system performance with the supply chain and financial requirements. The function of the strategic discrete-event simulation model is twofold: first, it can be used for setting-up high level requirements of the detailed discrete-event simulation model built in Experior from Xcelgo A/S; second, it can be used to make strategic analyses by using the detailed model as a virtual copy of the physical system to compare with for overall cross-validation and alignment purposes. A shared database connected to the actual system data enables the data exchange among the architecture components. The overall architecture is presented in Figure 2 while the strategic simulation model in Figure 3.

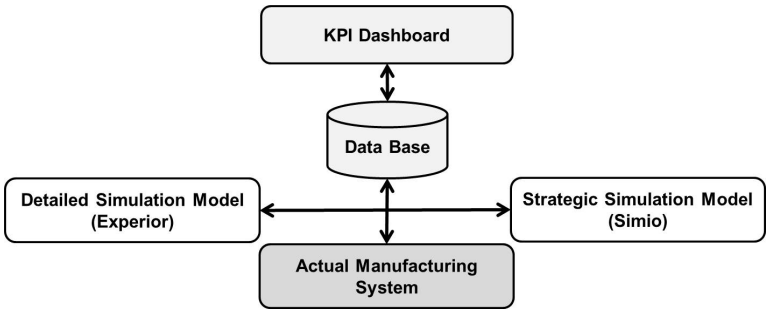

Figure 2: *Overview of the architecture for discrete event simulations and analytics*

The modular structure of the architecture provides the simulation experts and the end-users with the possibility to identify roles and tasks of all the involved professionals, usage profiles and goals, data flow requirements and formats, required output visualisations depending on the usage needs, easier and faster model (re-)building, maintenance, experimentation and analysis in complex decision making situations.

Recalling our digitalisation hypotheses presented in Section 2, we can preliminary argue that:

1. *Simulation models can be built and used by professionals not necessarily skilled on simulation modelling*. It appears that through the proposed application framework young professionals (domain experts and managers) are more inclined and naturally skilled in approaching simulation models and articulated performance dashboards most likely because they are already aware and familiar with visual technologies and usage of objects in dynamic tools such as, e.g., games or other professional IT tools. Detailed simulation models can be built within the context of a specific project or daily management tasks. According to our first findings, observations and user reactions, we therefore believe that simulation modelling skills are not strictly necessary in applications developed in the proposed way.
2. *Modular simulation models developed with the proposed approach can simultaneously answer questions based on standard and highly customised KPIs at multiple decision levels*. Standard KPIs are included in the modules. However, KPIs can also be added on-demand in specific module instances by simulation experts and, more importantly, combined for business intelligence purposes. So doing, high added-value predictive modelling for advanced analytics of systems performance can be carried out. More importantly, the dashboard of the modular architecture can relate highly detailed results of the simulations and the actual system with higher-level supply-chain and financial performance of primary importance of managers.
3. *Modular simulation models developed with the proposed approach can benefit domain experts and managers for daily management practices as well as strategic decisions*. We believe that both domain experts and managers can benefit from modular models and architectures because of the possibility to more easily and quickly combine and test different perspectives in the medium-short term or in the long term planning. Additionally, a validated simulation module or an entire digital factory model can be connected downstream to PLCs

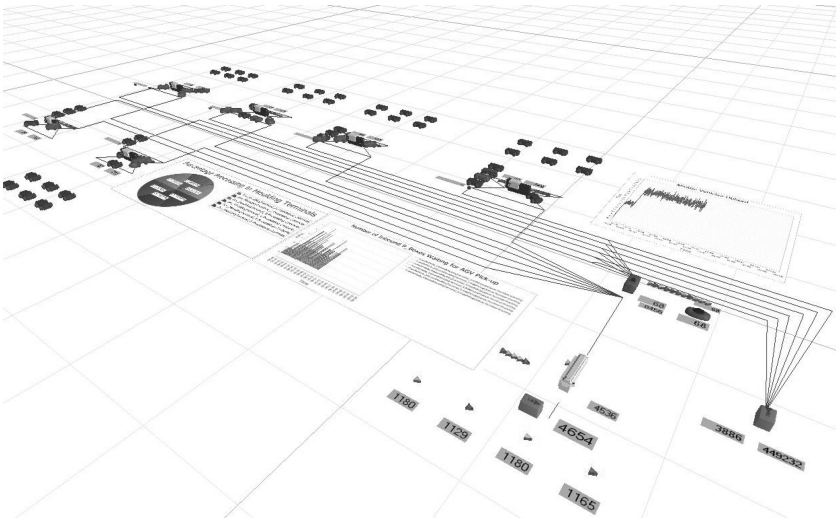

Figure 3: *Overview of the strategic discrete-event simulation model (Aalborg University uses Simio simulation software under a grant from Simio LLC).*

to optimise the equipment commissioning, thus realising virtual commissioning. A detailed simulation model can also share the output upstream with other tools for different analyses such as performance dashboards and higher level simulations to bridge potential alignment gaps with strategic production, supply-chain and financial goals.

5 Work Contribution

This work contributes to enhanced simulation usage and exploitation within the context of the digital factory by implementing modularity at two levels: model and architecture.

At the model level, modularity of simulation objects, control logics and data management allows the users to create digital models of physical systems that can be easily built, maintained, (re-)used and connected to PLCs to realise virtual commissioning. At the architecture level, modularity is implemented in terms of: potentially different decision levels supported by different simulation models; advanced analytics and customised visualisation; and actual manufacturing data management.

The proposed approach also contributes to the ways by which simulation models are developed and daily utilised, thus addressing the knowledge and organisational dimensions. A five-stage approach for the digitalisation demonstrator project has been implemented (Section 4.1). More importantly, we build upon the modularity-based simulation by Johansson (2006), and we try to extend it in terms of domain experts not necessarily skilled on simulation, decisions that can be addressed, and multiple usages in industrial practices, from manufacturing system modifications, to production, supply chain and financial management. This also supports stakeholder engagement, a better data management and a suitable level of detail for simulations which may represent issues for discrete event simulation (Jahangirian et al. 2010).

To the best of our knowledge, an overall approach concurrently addressing all the mentioned challenges in a single application case has not been presented so far.

The digitalisation hypotheses presented in this paper, whilst preliminarily discussed, suggest interesting insights and implications. First, the number of users and applications in manufacturing industry can significantly grow both within the context of a single company and across multiple (new user) companies because of the non-compulsory expert requirement as well as the economies of scale and scope in the development of simulation models. Second, in manufacturing industry, this may also open spaces for a concretely beneficial usage of simulation and analytics by small and medium sized players. Furthermore, such simulation-based digitalisation approaches and related potentials may represent an opportunity to spread a beneficial usage of simulation and analytics also in service industry and public administrations.

6 Conclusion and Outlook

The overall approach allowed conceiving a modular architecture based on modular detailed simulation modelling and advanced analytics. The work has been developed by using division of labour according to the roles of the involved professionals. A synergetic way of communication among them has been used to pinpoint practical goals and required results. The outcomes of the demonstrator developed for this application appear promising. On the basis of our assumptions, first indications and results discussed with the stakeholders, we believe that it is plausible to spread a quicker and user-friendlier usage of simulation in practical applications even if domain experts and managers are not skilled on simulation modelling. Multiple KPI analyses and decision levels as well as different planning purposes can be potentially supported.

Examples of definitions of these approaches to digitalisation of manufacturing systems and supply chains seem not well defined or aligned yet and need to be clearly linked with available definitions of digital, smart and virtual factory that can be found, for example, in (European Commission 2015; Constantinescu et al. 2006).

With this application, we aim to contribute with a normative approach to define innovative ways of developing simulation projects, using simulations in daily practices, and obtaining practical benefits. We believe that this is highly important in relation to the practical, beneficial usage of digital factory models and the preliminary principles of the Industrie 4.0 paradigm. Our future works will address and evaluate the execution of further experiments, the validation of the overall architecture, the efficiency of simulation usage and related analytics potentials in combination with other techniques and tools.

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