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OPTIMISED – Developing a State of the Art System for Production Planning for Industry 4.0 in the Construction Industry Using Simulation-Based Optimisation

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Abstract. Although it is not uncommon to have a predictive model of a factory, these models are often simplistic in nature. Such models rarely reflect the current operating performance of the system, use simple and separate data streams and do not go down to machine / workstation resolution. They can support production scheduling, but typically they are of limited use for optimising factory performance in response to changing external stimuli. The industrially led research project OPTIMISED develops a holistic factory management platform to react quickly and efficiently to unanticipated disruptions to the factory. The project consortium consists of 10 partners from various disciplines. The project develops three industrial demonstrators in three different domains. Strengths of this research project include the high technology readiness level of its demonstrators and their application with real data at an industrial scale. This paper presents the application of simulation-based optimisation to support production scheduling of the manufacturing process of one of the industrial demonstrators. The simulation model captures all relevant production constraints of the factory down to each machine and work station. The simulation model reads data from business information systems, live data from machines and data from retrofitted sensors on the shop floor. The optimisation uses the simulation model as a fitness function. As a result, both service level and production costs are optimised. The paper highlights the main characteristics of the solution, its application in real industrial usage scenarios and some of the main conclusions and opportunities for future research identified during its development.

Keywords. Simulation-based optimisation, transdisciplinary system, production scheduling, production re-scheduling, construction manufacturing.

Introduction

Explore Industrial Park (EIP) is one of Laing O'Rourke's manufacturing facilities that produces offsite manufactured components for various construction projects. These

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large components are then transported to the construction sites and assembled together on-site.

Production scheduling at EIP is the allocation of production orders for components to resources on the different production lines. Due to a variety of domain-specific constraints, computer-aided scheduling of the production at EIP is a difficult task. In a previous project, a professional production scheduling tool was introduced; however, these constraints could not be modelled appropriately in it. We investigate the application of a Simulation-Based Optimisation Approach (SBOA) for production scheduling at the EIP factory. SBOA incorporates optimization strategies and techniques into simulation design and analysis. Combining simulation and optimisation for scheduling promises to solve complex scheduling and rescheduling tasks [1].

Recent related work used a simulation-based approach for shop floor scheduling on a dynamic and flexible manufacturing system in an industry 4.0 environment [2]. However, this work did not incorporate optimisation. A dynamic scheduling system for steel making, refining and continuous casting production was designed by Pang et al. [3]. This work was mainly an optimisation scheduling strategy framework which did not include simulation. Other similar work in the area of scheduling include the work of He and Chen [4] but this did not incorporate real simulations. Cicconi et al. [5] focused on control and simulations. Currently, there is little work on solving a practical problem using SBOA on a large industrial scale in the heavy industry. About a decade ago, Dangelmaier et al. [1] worked on simulation assisted predictive-reactive system for scheduling and re-scheduling coupled with real-time control. This was applied on a small flexible production system which was subject to disturbances [1].

The approach presented in this paper was developed within the OPTIMISED[2] project; a consortium of research centres and industry partners. It focuses on developing and demonstrating a holistic factory management platform to monitor and to improve manufacturing and operations performance across three industry demonstrators. The approach was first deployed for the optimisation of train maintenance operations; SBOA was implemented to solve a train fleet allocation problem. The second demonstrator was developed and deployed to optimise the scheduling of a large machine shop. This paper focuses on the third demonstrator; an application of SBOA to production scheduling in a construction product manufacturing facility. This approach provides decision support for production scheduling in an environment with disruptions and multiple time horizons on the shop floor.

The project incorporates Industry 4.0 design principles. We address interoperability by developing and implementing a service-oriented infrastructure for information exchange between the shop floor, the associated enterprise systems and the SBOA solution. Information transparency and technical assistance are addressed by having the simulation model as a digital twin of the production process supporting the decision making in production planning and control. Also, the solution provides simulation/optimisation GUIs and production dashboards as a technical assistance to support users' decision making.

The paper is organised as follows. Section 1 introduces the industrial usage scenarios. Section 2 shows how the SBOA approach is integrated within the computing environment. Section 3 presents the simulation and optimisation engines and explains

[2] www.optimised-h2020.eu

the interactions between them. Finally, Section 4 concludes the paper by highlighting the current achievements, open research questions and future work.

1. Description of the Factory and Industrial Usage Scenarios

The EIP factory manufactures pre-cast concrete components that form a large proportion of buildings in construction projects. EIP produces these components in small batch sizes due to high variability. Factors at the construction site often influence production in the factory at short notice. For example, construction sites often delay the transportation from the manufacturing facility to site due to bad weather conditions. These delays can lead to the accumulation of finished components in the storage area and ultimately cause production to stop when storage capacity is reached.

Figure 1 is the floorplan of the EIP, which consists of three production lines, the finishing and the rebar areas. The three production lines are the High Speed Carousel System (HSC), the Bespoke Carousel System (BSC) and the Bespoke Static production area (BSS). The HSC is a pallet carousel system designed for fast production of standardised products. The BSC is a pallet carousel system designed to produce so-called bespoke products. The BSS is a production line with static moulds for production of bespoke architectural products such as columns, architectural edge beams, ramp edges and units too large for production on the BSC. One common theme across all production lines is the high labour expenditure and long makespan per component. The different degrees of automation within the manufacturing facility impose challenges on software support for production scheduling. Additionally, the high product variability and manual processes make the estimation of production times difficult.

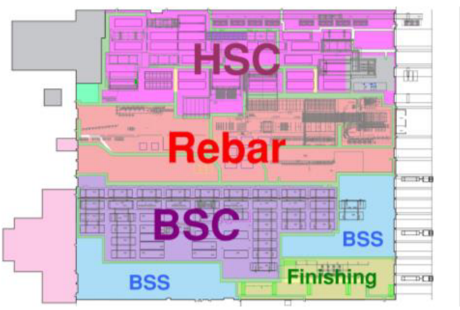

Figure 1. Floor plan of EIP factory

The following usage scenarios support two roles in the manufacturing facility: Schedulers and Production Supervisors. Each of the three production lines has a separate Scheduler. For a given week, a Scheduler is responsible for the definition of a line's daily production target and for tracking the production progress. A Production Supervisor is responsible for the operation of a work area and for meeting the daily production targets. Production Supervisors release orders to a production line, select workers for each shift and assign workers to jobs.

1.1. Usage Scenario 1 (Scheduling)

The EIP management agreed that the following Key Performance Indicators (KPIs) are to be optimised within the OPTIMISED project: The service level (the percentage of orders that are produced on time) and the production cost (the cost to produce all required components for a given week). Daily production targets are defined to reach a high service level. To define the daily production target, Schedulers work together with the Production Supervisors, as both have knowledge about different production constraints. Constraints include staff levels, resource availability, and time constraints. Currently, when Schedulers define a daily production target for each production line, they only document some of the relevant production constraints that influence production in a schedule. The impacts of production constraints on the daily production targets are assessed only using the knowledge and experience of Schedulers and Production Supervisors. This reliance on the knowledge and experience of individuals can increase their cognitive load, causing stress and potentially leading to errors. Production costs are currently not assessed explicitly during scheduling.

EIP requires schedules that explicitly incorporate all relevant production constraints while optimising service level and production cost. Such a schedule can support Schedulers and Production Supervisors in their decision making. Schedulers can use schedules to prove that they have defined a realistic daily production target due to the visibility of the relevant production constraints. All stakeholders can gain a better understanding of the impact of these decisions across all production lines and construction projects.

1.2. Usage Scenario 2 (Re-scheduling)

Currently, there is limited knowledge of the knock-on effects on production within and between production lines and projects due to disruptions. For example, strong winds may prevent the use of cranes in the yard for several hours. Once they are back in operation, it is crucial to define the most suitable way to use them so production targets are affected the least. Other ways in which Production Supervisors and Schedulers can react to disruptions include producing orders on a different day or increasing the number of workers to cope with a surge in demand. Currently, the knock-on effects and their mitigation are investigated and resolved in ad-hoc meetings whenever disruptions occur. The process for resolving disruptions in unscheduled meetings can cause time pressure and an increase in cognitive load resulting in suboptimal solutions.

EIP requires a system that supports Production Supervisors and Schedulers in re-scheduling production. The system should enable evaluation of “what-if” scenarios for the various decisions that can be implemented. In the example of the cranes given above, after the cranes are operational, the system should enable “what-if” analysis to determine whether increasing staff levels allows to still meet daily service levels and to determine the associated production costs.

2. Overview of the Software Architecture

The component-and-connector diagram, which represents the OPTIMISED system at runtime, is shown in Figure 2 and is described below.

- The Message-oriented middleware (MoM) provides the software infrastructure that supports sending and receiving messages between distributed systems. The MoM comes with a data store implemented on Apache HBase.

- The Optimisation engine solves instances of given factory production scheduling and re-scheduling optimisation problems.
- The Simulation engine is a simulation model of the factory. The engine simulates the implementation of a production schedule providing the simulated workflow information and associated KPI values. It ensures that valid solutions are generated.
- The Simulation/optimisation GUI and Ortems Launcher is a Graphical User Interface (GUI) to start SBOA and to manage its data inputs/outputs.
- ORTEMS is a standard software package for advanced planning. In ORTEMS, users can visualise and manually modify a specific production schedule.
- The Production Dashboard displays reports on production KPIs including energy-related indicators.
- Beacons Raw Data Processing Services and LOR Data Collector provide the interface between the MoM, and the Enterprise Systems and the factory data from sensors and machines.

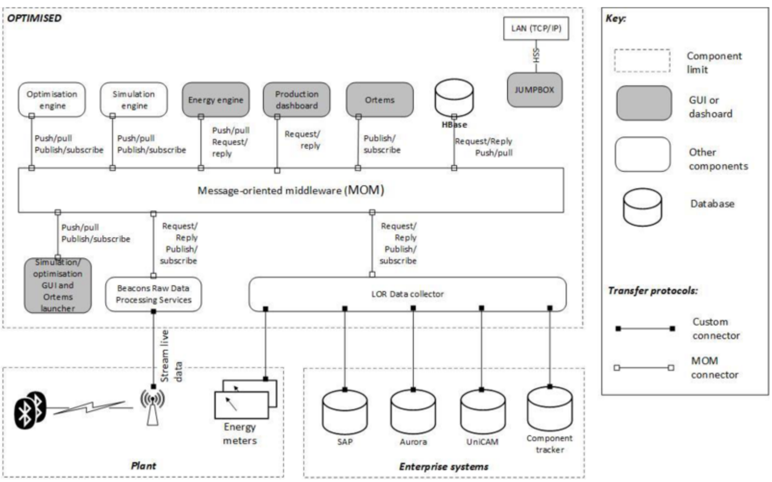

Figure 2. Component-and-Connector Diagram

Note that the Message-oriented Middleware is the infrastructure that provides the pathways of interaction between components. This middleware implements the following communication protocols: Publish/subscribe, request/reply and push/pull. Data from the factory and enterprise systems is collected by the Beacon Raw Data Processing Services and the LOR Data Collector modules, which perform data preprocessing before it is stored in the data storage. Users can alter the parameters of a problem instance and start a simulation-based optimisation on a specific data set using the Simulation/optimisation GUI and ORTEMS Launcher. This GUI displays information stored in the data storage, which allows the user to view, filter, select, and define an active production schedule. ORTEMS allows users to analyse schedules in detail, including machine utilisation and production efficiency.

3. Simulation and Optimisation Engines

The OPTIMISED project applies SBOA to create an optimised production schedule of the components produced at the EIP factory for a given week. This schedule maximises the service level and simultaneously minimises production costs. The simulation runs through a schedule and calculates its production KPIs. The KPIs are used as a fitness function for the optimisation. All production constraints are modelled only in the simulation to avoid any duplication in the optimisation. The schedule is designed to support the Scheduler in defining daily production targets (Usage Scenario 1, Section 1.1). Furthermore, the schedule is designed to support the Production Supervisor in achieving the daily production targets and to evaluate the consequences of disruptions on the shop floor (Usage Scenario 2, Section 1.2).

3.1. Simulation

In the context of the OPTIMISED approach for SBOA, the simulation is used to analyse and evaluate a schedule in a dynamic way. The schedule containing the orders and their specifics is run through in the simulation model. The simulation executes the process related to the schedule taking into account the constraints of the production facilities and mobile resources in multiple timescales. The simulation results for the schedule are analysed with respect to fulfilling the objectives. For this purpose, production KPIs are generated as an aggregation of the detailed simulation results.

The challenge of the simulation in production of construction components is the bespoke nature of the products and the different working methods on the related production lines. The bespoke nature of the products leads to constantly changing performance of the production facilities. A bottleneck determined in one project is not necessarily a likely bottleneck in the next project. Hence, determining fixed rules for production control cannot cover the effects of the variation of products. The integration of simulation into the data flow and constantly updating the simulation with current data helps managing these effects.

The working methods at the three production lines differ significantly and determine the different modeling focus. Two of the lines (HSC and BSC) are organised as a carousel having different levels of automation, the third one (BSS) is organised as flexible space used for manual process steps. The product and process flow at the carousels is determined by the transporting and conveying equipment whereas the process flow at the space is variable. This variety has to be covered by the simulation model.

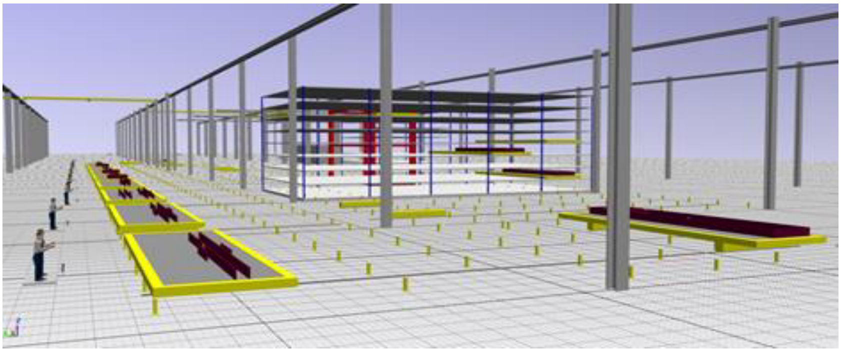

Figure 3. Simulation model of the Bespoke Carousel (BSC).

The simulation model is built using the discrete-event simulation tool Tecnomatix Plant Simulation by Siemens. In order to build the model in an efficient way and to consider the specifics of the precast manufacturing process, the object library STS_Precast was developed within the project and applied. The basis for this library is the STS library [6] for complex production and logistics, which covers a large set of objects for material flow modeling, model management, output analysis and data exchange. It has been developed as a result of interbranch cooperation since 2000 and it is used in various industries such as shipbuilding and at many universities. The STS_Precast library contains specific pre-defined simulation tools for precast production, such as a tilt table, precast rack, precast mould, pallets, conveyors, lifting trucks or pallet racks. These objects can be incorporated in the model and adjusted to the specific needs in terms of parameters or rules. In the model, the precast tools are applied in combination with the basic STS tools such as cranes, trucks, trains or space. Figure 3 shows a frame of the simulation model for the BSC production line.

Building a simulation model brings together many disciplines. The manufacturing operation is complex and has multiple dependencies with other processes. Consequently, IT, finance, logistics, management, sustainability experts and users such as production planners and supervisors must be involved in the development of the simulation model.

In order to consider the current production progress in the model, live data is imported. The live data is used to synchronise the simulation model with reality. This is achieved by starting the simulation in the past with historical data and creating all past processes according to the monitored live production data. When the simulation reaches the same point in time as that of the factory, the actual production progress is considered in the model. Based on the real production progress, the future part of the schedule can be predicted. Impacts of disturbances such as down times or material damage or of deviations in process time estimation can be evaluated.

Figure 4. Gantt chart of the production of components

The simulated process can be analysed in different ways. In this application the focus is on the analysis of throughput data and utilisation. The throughput data contains the start and the end of all simulated operations. The throughput data can be displayed as a Gantt chart (as shown in Figure 4) or compared to the planned dates and aggregated to KPIs. This is used to evaluate the *Service Level*. The analysis of utilisation collects and evaluates the states of the resources. The analysis can calculate the ratio of busy time during up time. The comparison of utilisation is used for bottleneck analysis for a specific period of time. Finally, the simulation calculates the *Production Costs*.

3.2. Optimisation

As stated earlier, the optimisation engine maximises the *Service Level* and minimises the *Production Costs*. This section introduces crucial optimisation parameters and presents the optimisation algorithm.

The following are the optimisation parameters. The optimisation engine reads in the simulation inputs for the start and end of the optimisation time horizon. A user can define, the number of iterations, the total number of times that the optimisation will send requests to obtain KPIs from the simulation. A user can define a pair of KPI weights, which are values assigned to each KPI in order to define their relative importance. The user can optimise all production lines simultaneously or individually.

In the *week mode*, the optimisation engine can schedule orders on any day within a given optimisation time horizon, which is typically a week. Alternatively, the optimisation engine can solve five individual one-day scheduling problems (*day mode*). The week mode promises better production KPIs, while the day mode reduces the search space considerably. On average there are 800 work orders to be scheduled weekly across all three production lines.

The optimisation engine can be started in two ways. A *time-dependent trigger* determines that the optimisation is carried out automatically at a pre-defined, specific time in the night with pre-defined optimisation parameters. This mode will optimise all the three production lines (HSC, BSS and BSC) for a given week. At night, the optimisation can run over an 8-hour period. The time trigger supports the scheduling (Usage Scenario 1, Section 1.1) by investigating an extensive search space to find a best fit solution. In the *on-demand optimisation mode*, the Simulation/optimisation GUI provides several options. The user can choose between week and day modes, they can optimise all production lines or individual ones and production constraints can be changed before optimising. This supports the Schedulers in rescheduling (Usage Scenario 2, Section 1.2).

The optimisation algorithm is a Hybrid Simulated Annealing-Genetic Algorithm (HSAGA). Simulated annealing (SA) is a metaheuristics technique for approximating the global optimum of a given function in a large search space. The optimisation approach employed in this project is partly adopted from the work of Kayode Owa et al. [7] where SA, genetic algorithm (GA) and particle swarm optimisation (PSO) were combined in a novel approach. In this project, both the crossover and mutation properties of GA were embedded into the HSAGA algorithm. The basic process for the HSAGA is as follows:

a) The HSAGA algorithm explores as many simulations runs as specified in the user input. For each simulation run, the optimisation modifies the sequence in which orders are released to a production line and the maximum number of available staff.
b) The optimiser normalises the production KPIs and then applies user-defined weights to calculate the final KPI.
c) From each simulation run, the final KPI is compared with the previous KPI to determine a better solution. The worse solution is discarded.
d) The better solution goes through chromosome change to produce a new solution by undergoing crossover and mutation processes.
e) Processes from b) to d) continue until the number of iterations is achieved.
f) The final solution is sent back to the MoM.

3.3. Simulation-based Optimisation

Figure 5 summarises the data flow between the simulation and the optimisation engines and the Message-oriented Middleware (MOM). The MOM provides a service that coordinates the data exchange between optimisation and simulation. To start the SBOA process, a time trigger or a user requests an optimisation. (1) The SBOA process starts with the MOM requesting an optimal schedule from the optimisation. The request contains the optimisation parameters to be used by the optimisation engine. (2) Optimisation initiates the simulation processes. (3 - 5) The initial simulation inputs are requested and received. (6) In each simulation run, for a given set of simulation inputs, the production KPIs are calculated. (7 – 8) The production KPIs are an output of the simulation and they are provided to optimisation. The optimisation engine calculates the aggregate fitness value from the production KPIs. (9) Based on the fitness value, the optimisation engine produces new simulation inputs for the next simulation run. (10) The simulation runs for each new set of simulation inputs. The procedure runs in a loop until the defined number of iterations is met. (11) The optimisation identifies and outputs the best solution. (12) The associated simulation inputs and KPIs for the best solution is sent to the MOM. Other components of the OPTIMISED solution then process the best solution to visualise it.

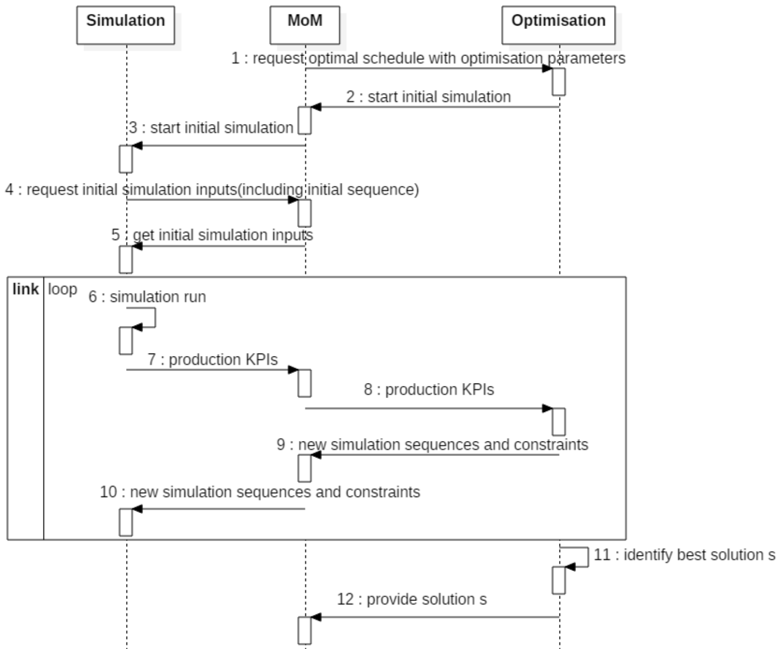

Figure 5. Sequence Diagram

4. Conclusion

This paper contributes to the state of the art by providing a detailed application of SBOA to the EIP factory within the construction manufacturing industry. The application was designed with the main production management team of the EIP. We presented two usage scenarios for production scheduling and rescheduling within the factory. We introduced the specification of the OPTIMISED solution for SBOA, in particular the interfaces of and interactions between simulation and optimisation.

Currently, SBOA is being implemented at EIP. We have undertaken first validation workshops of the simulation with the EIP stakeholders. We also tested the integration of optimisation with simulation. Next steps in the OPTIMISED project are to complete the implementation and to perform integration testing with the other components of the OPTIMISED solution. We plan to extended the SBOA approach to minimise energy cost in order to assess environmental impacts of the production. To this end, we started to deploy additional infrastructure for monitoring energy usage data so that energy consumption can be appropriately estimated. Finally, we will perform end-to-end system testing by feeding live production data including machine and sensor data into the system in order to produce schedules for the EIP factory. EIP production staff will validate the results in terms of technical effectiveness, efficiency and usability. This will allow us to fully evaluate the benefits of SBOA for our Use Cases.

We anticipate the following benefits from the application of SBOA: an increase in service level and a reduction of production costs including energy costs; explicit documentation providing transparency of production constraints; an improved understanding of the impact of production constraints on the production KPIs; decision support for Production Supervisors and Schedulers in the case of disruptions reducing the risk of cognitive overload. The design principles developed within the OPTIMISED project have already been deployed on different industries (railway, machine shop). This indicates that the applicability of this approach can be extended to other industries that can benefit from it.

In the course of the work we identified open research questions. Future research needs to identify efficient methods to incorporate domain-specific knowledge into optimisation methods. Further research will be necessary to improve the reliability of the estimation of the process times of manual operations. Economic, social and environmental impacts have been assessed in the work to date. Economic and environmental impacts can be quantified within the SBOA approach. However, the measurement of social impacts requires further research with relevant domain experts.

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