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Balanced Manufacturing (BaMa)

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1 Introduction

1.1 Project Goals and Focus

In 2013, when the project Balanced Manufacturing (BaMa) was initiated, the manufacturing industry focused mainly on availability, adaptability and productivity of production systems in order to increase competitiveness. The simultaneous increase in energy costs, legal pressure and public awareness and decrease in availability and security caused manufacturing companies to spotlight resource efficiency. Although a variety of methods and tools for optimization of singular aspects of energy efficiency within production facilities already existed, a systemic, comprehensive approach for analysis, evaluation and optimization of energy- and resource-flows within a production facility was lacking.

BaMa set its goal to develop a simulation-based method for monitoring, predicting and optimizing energy and resource demands of manufacturing companies under consideration of the economic success factors time, costs and quality. All relevant aspects of the facility (production, building, energy, logistics and management system) were considered.

The project started with a thorough system analysis and definition of the BaMa method. A modular approach was chosen that segments a production facility into "cubes". Cubes have a clearly defined interface and represent a certain physical behavior that contributes to the energy balance of the overall system. For demonstration, an experimental cube, representing a basic production-unit module was constructed. Based on cube-related energy and resource flow analysis, a method to aggregate a specific product-footprint was derived. The product footprint represents a product’s expenditures concerning cost, time, energy and the environmental impact such as resulting carbon emissions in the product life cycle phase within the factory.

In a next step, the BaMa method was implemented as a customized tool chain. The tool chain allows for energy efficient operation, design and refurbishment of production plants under competitive conditions, with regard to minimal energy and resource consumption. It contains three core modules:

Monitoring: data on resource consumption is aggregated and visualized.

Prediction: allows forecasting of overall energy demand of the plant based on the product-footprint and the production schedule.

Optimization: based on data and numerical simulation-models of the cubes, this part of the tool chain improves the plant operation with regard to defined optimization targets concerning energy and economic success.

Finally, the BaMa method and tool chain were deployed at production facilities of several project partners in order to demonstrate its functionality for multiple industry sectors and to ensure national and international visibility. In addition, guidelines for the BaMa implementation process in accordance with the ISO 50001 was developed. The objective of this process is the efficient energy management and optimization of production facilities.

1.2 Funding Research Program

The project BaMa was funded by the Austrian Climate and Energy Funds within the program "e!MISSION.at – Energy Mission Austria", which was administered by the Austrian Research Promotion Agency. The project was part of the Flagship Initiative Industry and specifically addressed the topic Energy Efficiency in Industry and Trade, which called for the development of industrial energy management systems. Compliant with the call-goal to contribute to meeting Austrian specifications in climate- and technology policy (20% increase in energy efficiency), BaMa enables companies to iteratively improve their energy efficiency by predicting and optimizing the demand. The integral approach of the project ensures a comprehensive optimization of manufacturing companies including all main energy consumers. Therefore, it additionally addressed other topics of the call such as: energy efficient production process design, the reduction of the energy input, and the reuse of waste heat within the examined production processes. Furthermore, it contributed to the call topic of intelligent energy networks by providing tools for operational energy management on the demand side.

1.3 Applied Methods and Structure of Project

In the first phase of the project the specific requirements for BaMa was defined and a method for system analysis of a plant in the sense of BaMa was developed. Use case definitions for the specific needs of the potential Balanced Manufacturing users were captured in close collaboration between the scientific and industrial partners. Therefore, an investigation of the industrial partner's production processes, energy efficiency goals, plants, and boundary conditions were conducted and literature, related work and projects were assessed for valuable input.

Based on the previous findings, a method for conducting a system analysis of a production plant in preparation for the implementation of Balanced Manufacturing was developed. The method was formulated at a generic level to ensure its usability in a variety of production facilities and relies on decomposition. A basic element of the decomposition consists of so-called **cubes**. Cubes bundle the boundaries of sub systems in terms of energy-, material- and information flows and were thoroughly defined to intersect the whole system into observable parts and manageable simulation modules. In order to build an executable simulation model out of the cube concept feasible formalisms and simulation methods were identified from the literature. Based on this theoretical specifications, test models of the simulation were built and iteratively expanded to more comprehensive prototypes.

Using one of the prototypes of the simulation, several optimization algorithms were tested concerning their computational performance and quality of results. Furthermore, the interfaces between the simulation and the optimization algorithm were defined, i.e. the target function, constraints and the degrees of freedom.

Parallel to the definition of the cubes, a product-footprint was defined. Each cube contributes to the product's energy, cost or time consumption within the production plant. Those accumulate to the product footprint. The product-footprint is made up of a high number of originally independent data streams that are aggregated in a time-synchronized manner. Methods for suitable data aggregation and fragmentation were identified and described. A set of rules concerning boundaries, in- and out-going flows and allocation of expenditures to products was developed in accordance with ISO 14067.

For verification and demonstration of the BaMa method physical cubes composed of machine tools, measurement devices and software for analysing the energy flows were engineered and installed at the laboratory of the Vienna University of Technology. All the relevant energy flows regarding the definition of the cube attributes and between the Cubes interfaces were investigated and monitored. An online life-visualization as well as a test simulation for a production scenario including optimization were implemented.

Parallel to the development of the BaMa method and the construction of the experimental cube the use cases of the industrial partners were developed into more detail and data was collected from the partners by analysis of system design data, monitoring data and additional measurements. Furthermore, a description of the data interfaces, aggregation and fragmentation paths were developed. The theoretical knowledge base for the Balanced Manufacturing application was formulated independently from tool implementation in order to make it useable or adaptable for different software tools and energy management system solutions.

Based on the theoretical rule base the tool chain was developed. The implementation followed established software engineering practices. At the beginning, a requirements analysis was conducted to clearly identify the advanced features of the future tools, define the necessary modifications to the existing toolset structures, and to deepen the understanding of the underlying production environment and the potential tool users (refinement of interfaces to cubes, other automation systems and user interfaces). Next, a simulation software was developed responsible for simulation of the cube models, data aggregation from all cubes; interfaces to store these data in databases. Together with a production plan, an energy consumption profile can be created. An independent footprinter was developed to aggregate the product footprint from the stored data. The stored data is the major input for the optimization. The tool chain was developed iteratively. From a first, prototypical version, it will be continuously extended and refined.

The functionality of the tool chain was tested by implementing prototypes of the use cases at project partners of the industrial user group. The user group consists of industrial partners of different industry sectors such as metal cutting or food processing who ensure by contributing their individual requirements the versatility of Balanced Manufacturing. In a final evaluation loop with the industrial partners, inaccuracies and further development potentials or necessities were identified. The evaluation specifically focused on significance of monitoring data, direct saving potentials gained by applying Balanced Manufacturing, accuracy of energy demand prediction and usability

Furthermore, a frame of reference management tool based on the ISO 50001 system with the object of efficient energy management and optimization (i.e. achievement of the energy reduction targets) will be developed to provide a convenient framework for anchoring Balanced Manufacturing in the operational sequences of the user.

A supporting process for the Balanced Manufacturing implementation that includes the classic phases of a change management process unfreezing, moving and refreezing will be developed and accompany the implementation taking place in WP 6. It will comprise rising of awareness within the management and staff, briefing and training on the tool of the involved staff and establishing Balanced Manufacturing into the everyday work routine.

1.4 Structure of this document

The following work will give an overview over the conducted work in the course of this project. When appropriate, respective chapters from the more detailed BaMa Documentation[1] will be mentioned for further information. After an introduction into the main ideas behind the project, the use cases will be described based on the applications developed in this project. Finally, some notes regarding the limitations of the developments will be given.

2 Project Description

2.1 Introduction

The manufacturing industry is one of societies' largest energy consumers. In the European Union, it accounts for 26% of the total final energy consumption [1] and the industrial sector promises major reduction potentials. [2] quantifies the achievable savings by reviewing numerous case studies between 30% and 65% depending on the industry sector. [3] also identifies major opportunities in balancing the electrical energy market by demand side management of large-scale industrial enterprises. Until a few years ago, requirements of manufacturing companies have dominantly focused on increasing availability, adaptability and productivity of production systems. [4] identified four classes of attributes, which determine the objectives and criteria for decision making in manufacturing: cost, time, quality and flexibility.

[1] http://bama.ift.tuwien.ac.at/static/downloadfiles/03_Bama_Documentation.pdf

However, the concurrent increase of legislative pressure, consumer awareness and progressively changing energy markets have caused manufacturing companies to streamline their production in order to increase the efficiency of resource usage, especially targeting energy consumption and CO_2 emissions.

Triggered by this demand, a variety of methods and separate tools for improvement of single aspects of energy efficiency within production facilities have already been developed (such as energy efficient machinery, optimization of stand-by-modes, use of waste heat, improvement of building hull, use of renewable technologies, life cycle analysis and sustainable product design). Research suggests that efforts in the direction of optimizing the energy demand of production companies are inhibited by a number of factors, one of them being the lack of supportive tools. A gap-analysis of existing research and industrial needs [5] identified two main development demands in order to enable efficient and effective energy management: production management with regard to energy efficiency and integration of energy efficiency performance criteria into information and communication technology (ICT) system. [6] identifies three main groups of barriers: economic, organizational and technological. Regarding organizational barriers, the authors see the problem mainly concerning lack of acceptance and accountability, which they propose to address primarily by cultural measures. To support these efforts, [7] proposes an energy management maturity model as a reference for self-assessment concerning the development state of the management system. Concerning economic barriers, [8] points out that the application of energy efficiency measures is often inhibited by long payback periods. This emphasizes the need for criteria to measure the economic impact of energy efficiency identified by [5], which according to the authors is a challenge that must be addressed on the technological level by exploiting the potentials of ICT technologies. [5] and [9] also agree on the potential of simulation in this respect. [9] sees major benefits in predicting energy and resource flows for large manufacturing systems and in this respect particularly highlights the simulation-supported optimization of production planning.

A number of publications concerning simulation-based analysis of energy use in manufacturing companies have been published in recent years. Some of them focus on the analysis of singular aspects of the system, mainly the manufacturing processes, others offer more comprehensive approaches, taking for instance the building or building services into account. A modelling approach to determine the energy required to produce single products is provided by [10]. [11] presents a systematic method to assess, model and reduce the energy demand of production systems especially targeted at small and medium sized companies. An energy-oriented simulation of manufacturing systems, based on process modules, which are characterized by an energy consumption behaviour, is proposed by [12]. Complementary, [13] offers a model to derive the energy consumption of machine tools from process variables. [14] proposes a comparable method based on Energy Blocks that represent the machine states. [15] presents an interdisciplinary approach to analyse the energy efficiency of production plants on manufacturing as well as on building level, which was later developed into a cooperative simulation tool, targeted at assisting the planning of new facilities [16]. [17] proposes a similar solution, which integrates building, HVAC, production management and material flow simulation. Applicable methods and modelling tools to analyse the interactions of manufacturing systems with their supporting energy infrastructure are investigated by [18]. However, all of the aforementioned modelling and simulation related publications are analysis-tools that are not integrated with ICT systems in order to provide feedback about energy performance on a daily basis.

Regarding methods to integrate energy related data into ICT systems [19] proposes an on-line energy efficiency monitoring of machine tools, which aims at increasing energy efficiency by scheduling and process optimization and promptly reports information about the energy performance. Ref. [20] proposes data exchange between Manufacturing Execution- and Energy Management Systems in order to optimize the joint operation of building services and manufacturing system.

Concerning integration of energy performance measures into ICT, the Carbon Footprint of Products (CFP) is a commonly used benchmark to quantify the environmental impact of products. CFPs are usually assessed for a defined product type or group on a one-year-basis. They are considered an important instrument for raising awareness on the customer sides as well as within the company. The latter is an important step towards achievement of energy efficiency, since research showed that especially management awareness is one of the factors significantly affecting the CFP in companies [21]. However, surveys of currently available standards and tools have brought up some issues with the reliability of results due to incomparability of different methods [22], intransparent calculation standards [23] and lack of reliable data [24]. The usual top-down approaches for footprint-calculations are even less suitable for support of sustainable plant operation, because they lack the temporal and spatial resolution necessary to base resilient statements upon them. [25] concludes, that one aggregated indicator is essential for communication, however, failing to provide the required detail to undertake a meaningful assessment. In accordance, [5] demands energy efficiency metrics on plant and process level and stresses the industry’s need for real-time data and knowledge-embedded processes leading to significant KPIs (key performance indicators) of energy efficiency. A CFP of adequate temporal and spatial resolution could simultaneously serve the purposes of an internal performance indicator as well as be a means of communication to stakeholders. Some research has been attributed towards extending CFP methodologies into the former direction or introducing alternative KPIs. [26] attempts to integrate a higher resolution into product footprints by means of simulation and [27] developed a set of energy-related KPIs that allow the interpretation of cause-effect relationships.

Thereby it can be concluded, that there is a large need for development of ICT-based energy-optimization tools on the one side, as well as of meaningful energy performance indicators in order to incorporate effective energy management into production management.

In order to bridge this gap, the project BaMa aims for the development of integrated tools to assist energy-aware steering of a plant during operation, by enabling monitoring, prediction and optimization of the plant's energy demand. As a basis for this tool-chain, the project introduces an innovative, comprehensive modelling approach, utilizing a modular concept of cubes, for representation of complex manufacturing facilities and processes. Using this approach as a basis, the developed tool-chain enables prediction and optimization of energy demand through simulation, which is not possible with previously existing tools. Through application of the aforementioned concept, energy efficiency can be coupled with the entrepreneurial success factors of production time, cost and maintained quality and a meaningful indicator can be derived.

2.2 BaMa Functionalities and Documentation

First objective of the project was to precisely identify the industry's demand and derive the requirements of the tool-chain. In order to derive these a use case based approach, common in software engineering, was chosen. Use cases derived from industrial partners' needs and the knowledge base built in previous projects were used to identify the requirements and develop a methodologically sound approach to analyse and prepare a production plant for the implementation of Balanced Manufacturing. As approach for the system analysis, splitting the plant into modular parts called "cubes" was chosen. Based on the theoretical method a simulation method was chosen and a suitable optimization algorithm identified. Furthermore a suitable approach for the aggregation of the product footprint was developed. All the theoretical results of the project are integrated into a target group oriented communication strategy. The intention of this form of documentation is to adjust the level of detail to the needs of specific user target groups on order to increase the readability of the BaMa specifications.

Three main user groups were identified:

BaMa users: This group represents the industrial users, who may be interested in the implementation of BaMa at their plants. Within the project, this user group is represented by six industrial partners, which contributed the use cases (Infineon, MPreis, Haas, MKE, GW St. Pölten and Berndorf Band). The main scope of the documentation for this user group is to give a brief overview of the methodology and functionalities of BaMa and to provide a basis for the decision, whether BaMa provides a feasible solution for the specific problem a user might want to address.

BaMa consultants: This group consist of companies that offer consulting services and/or technical assistance for the implementation of BaMa tools at factories. In many cases, the provider (see below) may also serve as the consultant. This part of the documentation mainly focuses on the aspects that need to be taken into account, when implementing BaMa into a specific factory.

BaMa providers: The last target group consists of companies that want to develop BaMa tools. In the project, this user group is represented by AutomationX and Siemens. In this part all the specifications, formulation and algorithms necessary to do so are described. Of the three levels, this is by far the most detailed one.

The user group oriented documentation of the BaMa method can be found in the annex of this report. Therefore, the project results contained in the documentation will only be summarized briefly in this section.

First in a series of workshops with the industrial partners, their key issues and problems were identified. In the course of this process a structured questionnaire was developed. It contains questions designed to map out the users problem scenario, the specification of the systems under study, an implementation roadmap and a business case. The questionnaire can be found in the BaMa documentation Chapter 2.2.1. Based on the findings of the use case partner workshops a description of the functionalities of the BaMa method and tool-chain was composed. A detailed description of the use cases themselves can be found below.

As mentioned previously BaMa's main objective is the coupling of sustainability with competitiveness in industrial production, by finding a balance between energy and cost efficiency. To achieve this goal a software tool-chain integrates the Balanced Manufacturing approach into industrial automation systems, as support instrument for energy aware steering of a plant during operation.

Two aspects distinguish the scope of the BaMa approach from that of other energy management systems and optimization tools discussed above. First is its comprehensive character. It addresses the production systems, the building, the energy systems and the logistics. Secondly, the aim of the BaMa tool-chain is not to serve as a design or analysis tool, which focuses either on the design of new production facilities or on the assessment of existing systems and identification of improvement potentials. Objective of the tool-chain is to assists in operating a production facility in a balanced, energy efficient way, much like an advanced planning and scheduling system would support a cost and/or time efficient production process. Cost, time, quality and flexibility are usually the planning targets of common scheduling tools. Balanced Manufacturing adds another factor, considering the environmental impact. Therefore, briefly, BaMa introduces energy as a steering variable into the plant's operational planning.

In order to meet the discussed challenges and integrate all the desired functionality the BaMa tool-chain contains three core modules:

Monitoring: Data on resource consumption are aggregated and visualized. Monitoring results serve as a reporting document and help to identify technical and infrastructural optimization potentials. This makes BaMa compatible with the requirements of the energy management standard ISO 50001, which is based on the Deming Circle or Plan-Do-Check-Act principle and therefore demands for a mechanism to assess the targeted results.

Prediction: Based on data and numerical simulation-models of machines, equipment and infrastructure, this part of the tool-chain allows forecasts concerning the overall energy demand of the plant based on the production plan and other forecasting data (e.g. weather information). This feature is especially useful for predictive planning of energy demand and production. It can therefore support demand side management and the integration of production sites into smart grids.

Optimization: Based on the results of repeated simulations, an optimization algorithm identifies improved plant operation strategies with regard to the optimization targets energy, time and costs. This happens under consideration of restrictions such as resource availability and quality requirements. The optimization aims specifically at minimizing energy demand by using synergies, peak load management and optimized use of available equipment.

As mentioned above, the BaMa software tool-chain is a tool that will be designed to support the operation of a production facility in a balanced, energy efficient way. Therefore, BaMa is ideally utilized periodically during the operation of the plant in order to compute optimized strategies for the plant operation. To ensure the tool-chain's functionality in this respect, it will generally have to be interfaced with the automation systems of the company. There is a variety of challenges that can be addressed with the help of BaMa. Figure 1gives an overview of conceivable use cases for the application fields and the different modules of BaMa in the four fields of action.

	Machines and production process	Building	Energy system - TBS	Logistics	Overall Application
Monitoring	• Monitoring of energy demand of certain production processes or steps • Condition monitoring via energy data analysis	• Monitoring of room conditions in order to avoid violations of comfort conditions	• Monitoring of energy flows within company • Monitoring of energy converters and storage charging level • Error detection	• Monitoring of energy demand of transport processes and storage • Condition monitoring of transport systems	• Comprehensive energy monitoring and reporting tool according to ISO 50001 • Calculation of gate-to-gate product footprint
Prediction	• Prediction of production energy demand based on production plan	• Prediction of heating and cooling energy demand based on weather data and production schedule	• Prediction of demand of different forms of energy based on demands of production, logistics and building	• Prediction of energy demand for transport and storage based on production schedule	• Prediction of total final energy demand • Intelligent connection to smart grids
Optimization	• Peak load management • Scheduling of tasks achieving minimized labor and energy costs	• Optimization of heating or cooling schedules according to production plan and weather	• Optimized operation strategies for available equipment • Optimized use of storage potentials	• Minimization of covered distance by means of transport • Energy or cost optimized timing of transport activities	• Global energy or cost optimum considering degrees of freedom in all action fields

Figure 1: Use cases for BaMa according to modules and optimization fields

A detailed description of the types of problems BaMa can address and the limitations of the tool can be found in the BaMa documentation Chapter 2.1.1 – 2.1.3.

2.3 BaMa Modelling Method and Simulation

As mentioned in the previous section, predicting the energy demand is one of the core functionalities of BaMa. The prediction is based on data and numerical simulation-models of machines, equipment and infrastructure. Due to the chosen tool-chain functionalities, the model and the simulation are the core parts of the tool-chain and their structure and characteristics must be well considered.

The BaMa modelling method is the basis for the tool-chain and represents the core concept of the BaMa approach. It has two main purposes:

i) serve as a guiding principle for analysing a manufacturing system prior to the implementation of BaMa, and
ii) serve as a concept for the development of models of the production facilities, which are prerequisites for the simulation the tool-chain is based upon. Both purposes result in certain demands regarding the method and have to be taken into account when designing the model.

From the modelling and software perspective, it needs to be taken into consideration that the modelling approach shows the necessary flexibility to adapt the model efficiently to represent a unique plant. A number of researchers concerned with medium to large scale simulation models have suggested decomposition or modularization approaches at model design level, to ensure model flexibility and reusability of model parts [28]–[30]. Similar design principles are recommended in object-oriented software engineering, where apart from modularization and decomposition also encapsulation and information hiding play an important role. Encapsulation aims at hiding internal details towards the external and only providing necessary functionalities and properties. Communication usually takes place via interfaces. As long as the interfaces remain unchanged, encapsulated system parts can be exchanged without affecting the overall system behaviour [31]. This suggests that a modelling approach based on decomposition and encapsulation could be developed into an efficient framework for BaMa.

From the system analysis, perspective the chosen method must be designed to address the high system complexity and heterogeneity. This can again be accomplished by decomposing the system into smaller parts following the divide-and-conquer principle. The chosen method divides the overall system from an energetic point of view into well-defined manageable modules, which then allow a focused system analysis independent from the surrounding environment. The approach BaMa follows is formulated at a very generic level to ensure its usability in a variety of production facilities and the reusability of components.

The basic module of the system analysis is called “cube”. Cubes have a clearly defined interface and represent a certain physical behaviour that contributes to the resource balance of the overall system. This approach, inspired by common approaches from fluid mechanics or thermodynamics, was chosen over the usual process approach, because it corresponds more intuitively with the paradigm of modularization. Cube boundaries bundle balances in terms of energy, material, cost and information flows in the same physical place and therefore decompose the whole system into observable parts. A cube can be for instance a machine tool, a chiller, a baking oven, the production hall or a utility system. Figure 2 illustrates the concept of cubes.

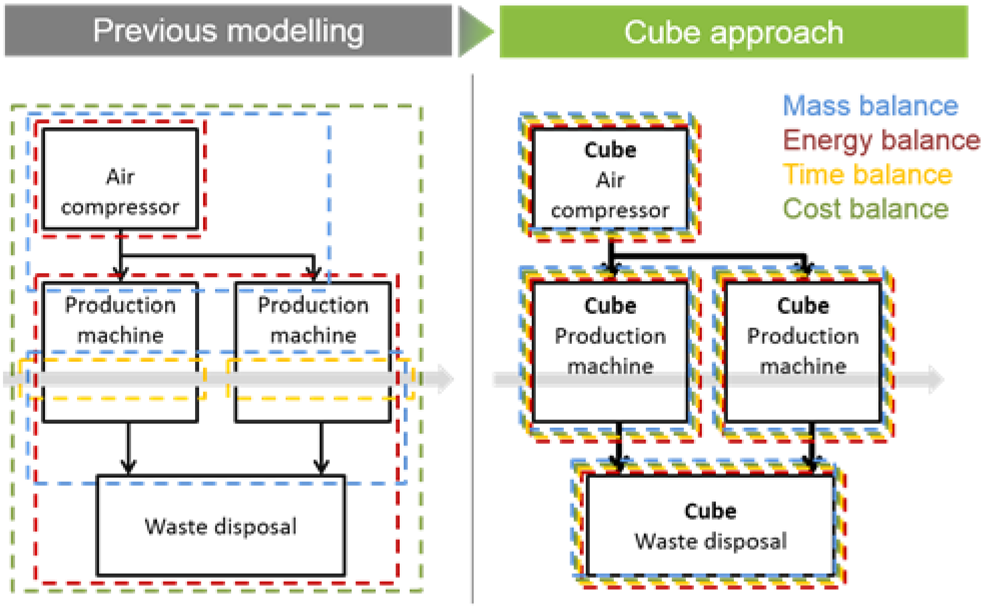


Figure 2: Concept of cube decomposition

Figure 3 gives an overview of the interfaces of a generic cube. Information flow provides operating states and monitoring values for the higher-level control as well as control actions for the cube module. All necessary energy flows (electrical, thermal, etc.) are represented together with their respective CO_2 conversion factors and are quantified inside the cube boundaries using balance equations. The material flow incorporates the immediate value stream (e.g. product, work piece, goods). It enters the cube with an assigned footprint. During the stay of the product in the cube, the cube's resource expenditures concerning this product are accumulated and assigned to an updated footprint upon exit of the product. This leads to the necessity that the value stream has to be described as discrete entities. Uniting discrete and continuous modelling techniques in the cube models is one of the main challenges in implementing the methodology. In principle, every cube in a production facility (building, production plants, energy converters etc.) can be represented by the generic cube model, featuring the described interfaces, which ensures their versatile composability.

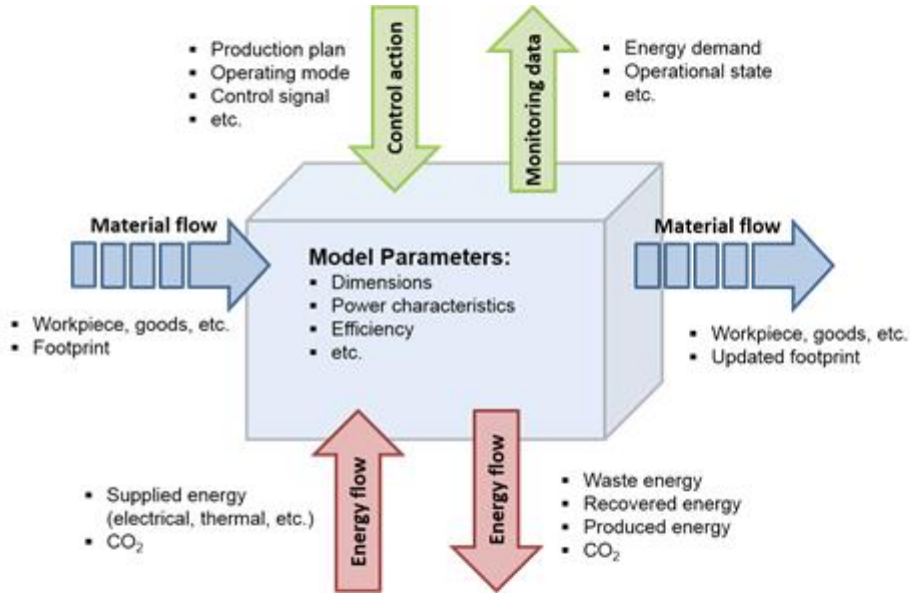


Figure 3: Cube interfaces

Cubes are on one hand an analysis tool for the real production system, which is mentally divided into cubes (real cubes). On the other hand, the cubes are the building blocks of the simulation model, which realizes the prediction of the behaviour of the plant as results of a dynamic simulation. The results of the simulation form the basis for the optimization. Therefore, the prediction and optimization use models of the cubes (virtual twins of the real cubes) in order to simulate the behaviour of the system parts. Figure 4 shows the relationship between real and virtual cubes in the simulation environment and the integration into the overall automation system architecture. On the lower right, the real system with imaginary cube boundaries is shown. The real system interacts with the plant’s automation system via interfaces. Sensors measure data and actors apply control actions. The automation system routes data between the BaMa tools and the real system, supplies additional data e.g. from enterprise resource planning or manufacturing execution systems and integrates BaMa into the control centre.

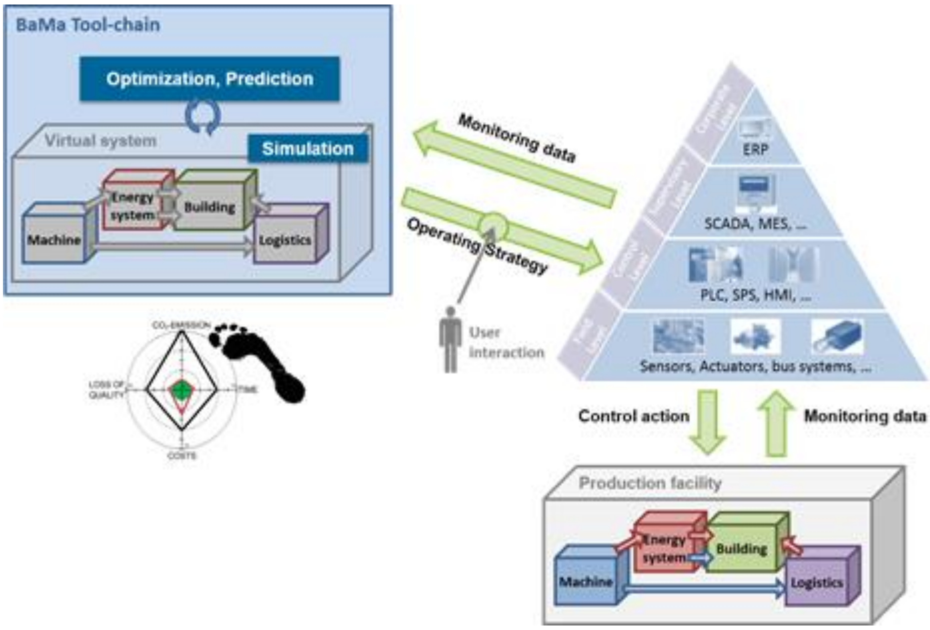


Figure 4: Architecture of BaMa tool-chain

Moreover, cubes also serve to organize the knowledge base for individual modelling tasks by providing a concept for elementary parts of a manufacturing system that in some way contribute to the overall resource balance of the system and their possible relationships to each other. In can be an effective measure to construct knowledge bases by organizing knowledge and providing a mechanism to understand problems, object statements by harmonizing specialized terminology of domain experts, and provide a valuable support in order to determine consistency, completeness and adequacy of a model.

In order to emphasize the use of cubes as a communication tool, subcategories of cubes are introduced. Although every cube in a production facility can be represented by the generic cube model, cubes representing different parts of the system can be described with properties that are more refined or certain interfaces can become obsolete. Therefore, to respect these peculiarities of cubes and make matters more tangible for users, a rough categorization of subclasses is introduced in Figure 5. A more application-oriented description of cubes and how to decompose a facility into cubes can be found in the BaMa documentation Chapters 2.1.4 and 3.1.

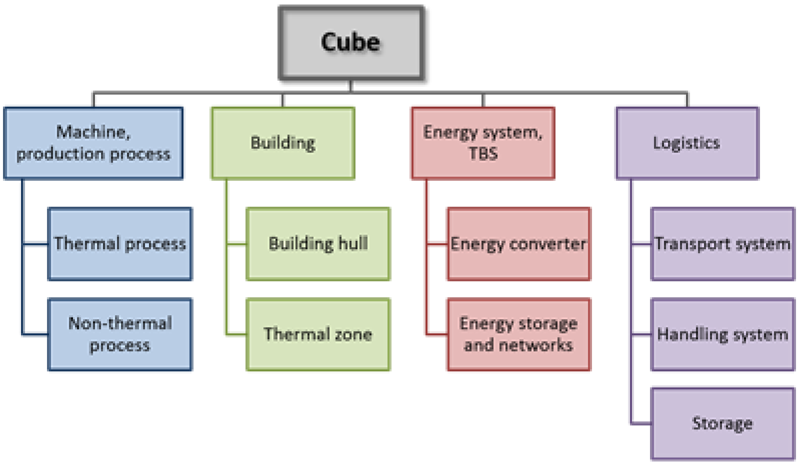


Figure 5: Categories of cubes

As mentioned above cubes unit continuous energy flows and discrete material flows. Uniting discrete and continuous modelling techniques in the cube models is one of the main challenges in implementing the method as an executable model. The model components (the virtual cubes) are of hybrid nature. This means, that they unite discrete and continuous modelling paradigms. Therefore, the overall hybrid model cannot easily be split into modular discrete resp. continuous subsystems. By following an approach for integrated hybrid, simulation instead of using e.g. co-simulation (like in [32]), modularity and unity of virtual cubes is preserved.

After evaluating different formalisms and descriptions, DEV&DESS (Discrete Event and Differential Equation System Specification) [33] as a hybrid DEVS (Discrete Event System Specification) formalism [34] based on Parallel DEVS (P-DEVS) [35] provided a suitable choice. The formalism is on the one hand open and established. On the other hand, it is also generic enough to allow incorporating different domains of engineering. Implementing the simulation models is based on an open and documented formalism that allows not only a formal and complete description of hybrid model components and subsystems but also a transparent implementation of the simulation engine for handling events and equations. Especially the second aspect is crucial in order to be able to include simulation functionality into the BaMa tool-chain without having to rely on third party or proprietary software. A detailed description of how the simulation was implemented using the DEV&DESS formalism is given below in the section about the BaMa prototypes and in the BaMa documentation.

Based in the DEVS&DESS formalism and the cubes' generic interface specification the virtual representation of the cubes was formalized. For this purpose, the two main facets of a cube are differentiated: its interfaces to the other cubes and its inner behaviour. Template based cube descriptions were introduced to obtain a unified documentation. They feature a graphical description of the interfaces, interface, variable and parameter lists and a description of the cube behaviour. Moving from the interfaces to the inner behaviour of the cube, we have to model energy flow as well as material flow and information flow aspects inside the cube. The energetic behaviour of a cube is determined by balance equations, which, in combination with other differential and algebraic equations for energy-related internal variables (e.g. temperature), provide a continuous model description. This discrete behaviour is described by state machines. The continuous and discrete aspects of a cube are not always clearly separated, but instead are tightly coupled and interfere with each other, e.g. when a temperature change leads to a state transition, or the attribute of an arriving entity becomes part of the differential equations. A more detailed description of suitable modelling approaches and an example for cube formalization can be found in the BaMa documentation Chapter.

2.4 BaMa Product Footprint

Since BaMa aims to balance cost, energy demand and CO_2 emissions, a way to assess these quantities in a fair way is necessary. To achieve this goal, a method for calculating a product footprint from the bottom up has been developed. The indicator product footprint has been chosen since it fits the Cube method well, especially regarding the hybrid approach of using entities to describe products. Each entity can carry a footprint, be it CO_2-emission, energy demand, cost or any other quantifiable feature of interest. However, the standard approach of calculating a product footprint is top-down, meaning that the global expenditures over a year are taken and distributed to products evenly. This is rather limiting. Using the modelling approach of the Cube method and the data obtained by the BaMa prediction and monitoring, detailed information about a production facility are available. Aggregating this data allows for a high degree of detail in assessing the impact different products have on the overall expenditures and the flexibility to choose the time intervals as needed.

The proposed product footprint focuses on the manufacturing stage of the product lifecycle, as is in accordance with the goals of BaMa. Figure 1 shows different stages of the product lifecycle, from cradle to grave, focusing on the manufacturing of a product. Different types of footprint can be assessed, most notably CO_2-emissions or cost. The partial footprint obtained represents a gate-to-gate footprint of the manufacturing plant and can be used in a broader footprint study to complete the entire product lifecycle.

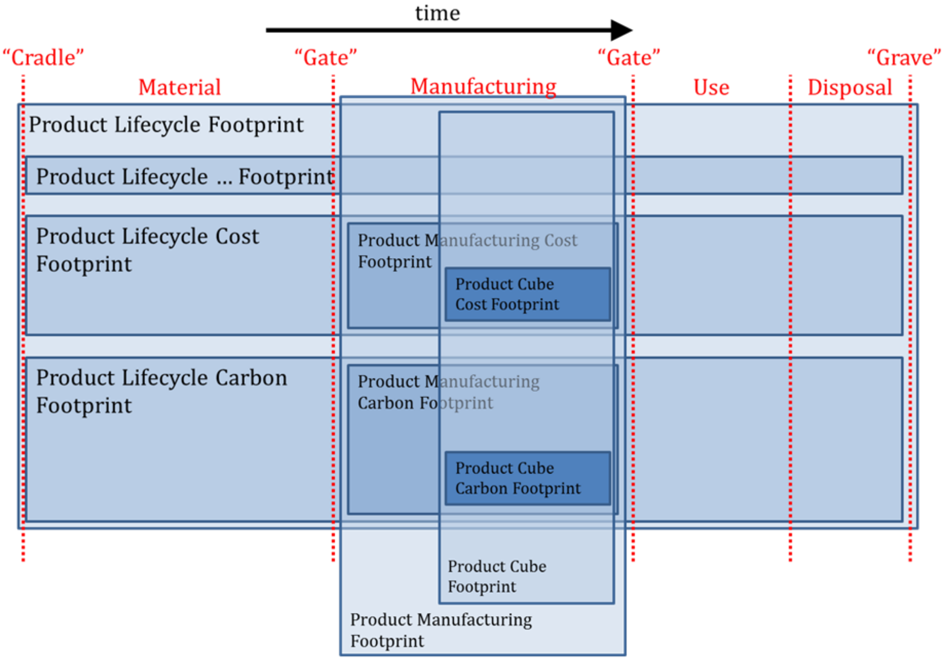


Figure 6 Product lifecycle from cradle to grave of different footprint categories.

2.4.1 Basic footprint method

The basis for calculating the product footprint is using data of the energy flows between cubes. Each energy flow carries footprint densities representing qualifiers for valuing the energy flows in regards to different footprint types. For example, the carbon footprint density of an energy flow would be measured in gram CO_2 equivalent per kWh.

When calculating the footprint for a given time period, the Cube footprints are determined by collecting all energy flows and footprint densities of a Cube, integrating them over the time period and distributing the resulting footprint to the entities inside the cube (direct footprint attribution). If no entities are inside the Cube, the footprint is delegated to the next highest Cube in the hierarchy (footprint delegation). For example, if a production machine Cube is situated inside a thermal zone Cube, the footprint of the production Cube not being able to be distributed is delegated to the thermal zone Cube. In some circumstances, it is required to attribute footprint to a group of entities, even if they are not present inside a Cube (group attribution). Examples can be the footprint aggregated during setup of a machine being attributed to the batch being produced after the setup or administrative cost being distributed to all products produced in the factory.

If multiple entities are inside a Cube, the distribution of the footprint needs to be done fairly. Different products need to be able to receive different shares of the Cube footprint to account for different size, value or other attributes of products. This is done be using weights. Weights are attributes of entities and discern the attributes of area, market value and added value. The area weight denotes the area required to store, transport or produce a product and is a good indicator of the share a product carries of the footprint of thermal conditioning of the factory. The market value is an indicator to discern primary products of a process to secondary or waste products. The added value weight represents the work invested into the making of a product.

2.4.2 Implementation

When using the BaMa prediction to calculate the performance of a production plant it is advantageous to implement the footprint method into a software tool as well in the form of a module called "footprinter". However, it is advantageous to use it as an extra tool rather than integrating the footprint method into the BaMa prediction altogether. Especially in cases, where the simulation is coupled with the optimization module, the footprint on a per piece basis is not needed and therefore only adds a performance overhead. Secondly, the footprinter can be used outside the realm of BaMa prediction, for example using monitoring data or even doing a footprint study by hand.

The footprinter uses as inputs the hierarchy of the Cube model, the data of energy flows including footprint densities and a list of footprint events. The footprint events represent the path of the entities through the facility; whenever an entity enters or leaves a Cube an event occurs.

The algorithm calculating the product-manufacturing footprint goes through the event list in chronological order. For every time interval spanning between two events, the Cube footprint is calculated for every Cube, starting at the leaves of the hierarchy tree (i.e. the outermost or lowest Cubes in the hierarchy). If a Cube contains entities the footprint is distributed to them, otherwise the footprint is either delegated to the next highest Cube in the hierarchy or attributed to a group of entities.

2.4.3 Proof-of-concept

Two proof-of-concept studies have been performed to show the capabilities of the bottom-up footprint method. The first study was conducted manually to explain the basic functionality of the method in a more relatable way. The second work was the implementation of the footprinter as a software prototype. In both cases, scenarios were calculated to show the importance of a high spatial and temporal resolution, especially regarding the sensitivity of the results to changes in production schedule and ambient condition. Detailed information on the method, the implementation and the results of the scenarios are published and are being published as scientific publications.

2.5 BaMa Optimization

The optimization module that utilizes the hybrid simulation as an evaluation function was developed in two phases: First, different metaheuristics that are suitable for complex multimodal (featuring local optima) fitness-landscapes were evaluated using identical scenarios. Second, the best performing heuristics from phase one were then enhanced and customized to provide an optimal fit for the given optimization framework and model behaviour.

The optimization framework, depicted in Figure 7 consists of the following parts:

- Hybrid simulation module (from AutomationX and Vienna University of Technology)
- Scenario: The production scenario comprises an initial production plan, a demand plan and a chosen season (weather influence)
- Input file: this parameterized file includes the concrete information for the given scenario and is called by the simulation module
- Results: The results from one simulation run serving as feedback from the simulation module
- Target function: Evaluates the results from each simulation run and represented by one → “fitness value”, giving a final information about the quality of the actual solution
- Production Plan Generator: As depicted in Figure 8, this module generates a valid production plan out of the chromosomal structure of the storage (and oven) vectors. Those are filled into the input-file before the simulation is executed again.

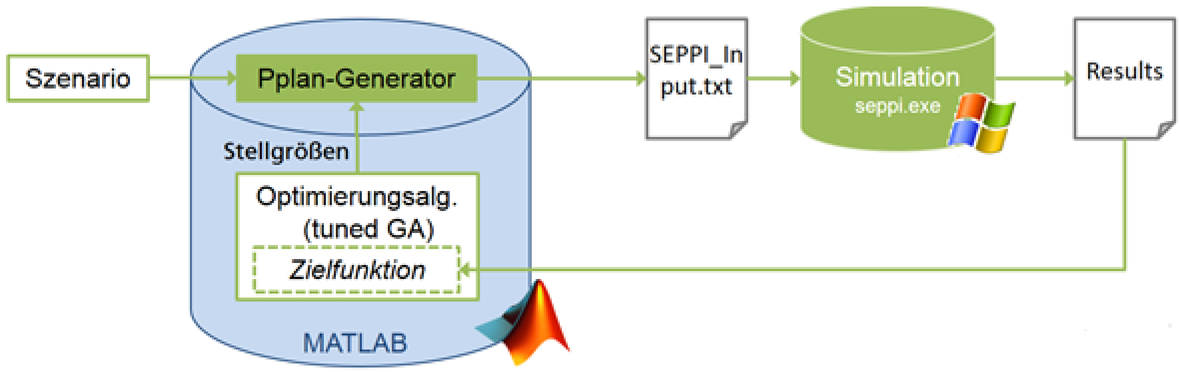


Figure 7: Structure of the optimization

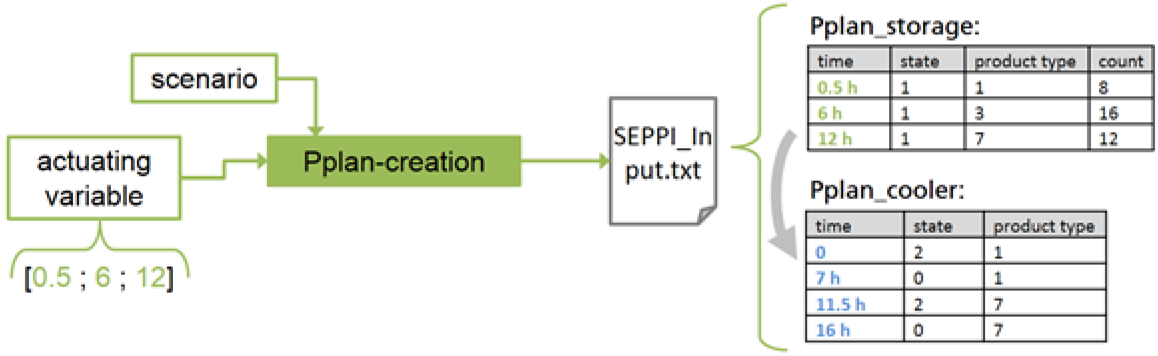


Figure 8: Production Plan Generator

At the end of the development process, a Genetic Algorithm (GA), with a set of tuning and customization measures for optimal optimization performance, emerged as the best performing solution. In a simplified test case, the optimization was able to improve the objective function of the optimization by up to 30%.

Concerning the multi-criteria objective function for the optimization, the following function used in case studies:

$$f(x) = \sum_{j=1}^{j=m} \omega_1 f_1(d_j) + \sum_{i=1}^{i=n} \omega_2 f_2(c_i) + \omega_3 n_2 k_1 + \omega_4 n_3 + \omega_5 n_4 + \omega_6 n_5$$

$\omega_1 - \omega_6$	part-goal weights
n	total number of production lots
m	total number of product types
$f_1(d_1)$	evaluation function for late deliveries on product type level [€]
$f_2(c_1)$	evaluation function for storage costs on production lot level [€]
$n_2 k_1$	accumulated overall energy costs [€] (including CO_2 penalties)
n_3	deviation between production demand and production output
n_4	oven aggregated uptime [€]
n_5	accumulated lot changeover-costs [€]

The objective function is normalized to calculate a cost value denominated in Euro. The part-function calculates storage costs for goods finalized before the delivery date and penalty costs for delayed deliveries as a function of the order completion time. The third part considers the energy consumption – the overall energy costs are calculated as a combination of the actual energy cost per energy source and a cost value for the associated CO2 emissions. Concerning the energy costs, a time-continuous progress curve (within a day, e.g. a week, different seasonal effects) was considered and observed within BaMa. The actual spot-market prices used for energy. The energy cost for cooling in the case study is calculated using the consumption data of the electrically powered coolers. For the heat production the actual costs for the company was used. Concerning the cost value for the associated CO2 emissions, the energy usage per energy source was combined with corresponding conversion rates for Austria. The third part of the objective function evaluates penalty costs for unsatisfied demand during the simulation and the fourth penalizes unfinished goods at the end of the simulation.

2.5.1 Adaptations to the Optimization Module

The major components of the optimization, a customized/tuned Genetic Algorithm (GA) remain unchanged. The customizations comprise a guided search by adapted operators in the GA, a memory function from the Tabu Search algorithm, a mixed integer optimization (default value 1), and hybridization by combining the GA with the PS and determining the optimal population size.

The most prominent adaptation of this basic optimization is the separation of the optimization procedure into two phases – this is a measure to improve the runtime of the optimization. Due to the large search space created by real life production systems, it proved beneficial to enable only the sequencing and scheduling of orders in the first phase. This is followed by a second phase with a fixed order sequence, during which the operation time windows for machines and equipment in the periphery are being shifted and contracted, mainly in order to minimize the energy consumption. In the first phase, the only necessary constraint is to have positive order release times. In the second phase, overlapping processing on any given machine has to be prevented as well as ensuring the operating times on every machine are at least as long as the minimum processing time for each production lot on the same machine.

A second major adaptation is the introduction of a production plan generator (PPG), the goal of which is to minimize the number of practically infeasible solutions created by the optimization (GA). In phase one the PPG is called after every simulation run for every intermediate solution. Between phases one and two, it is called again to ensure feasible oven operating times and ensuring the linear constraints are not violated. In phase two, the PPG also receives optimized oven times for every intermediate solution to calculate the operating times of the remaining equipment.

2.5.2 Results from Optimization

Although scenarios with 1/7/30 days simulated time have been conducted, the most usable anticipated application case right now is the one day planning horizon, thus the presentation of results will focus on the one day scenarios.

Although scenarios with 1/7/30 days simulated time have been conducted, the most usable anticipated application case right now is the one day planning horizon for the case-studies, thus the presentation of results will focus on the one day scenarios. Part (a) from the Figure 9 shows the influence of different seasons, corresponding weather conditions and electrical energy prices (spot-market) on the optimization potential. Plot (b) shows the part goal trends during the course of the optimization by displaying the mean values for each generation of a GA population. The latter diagram shows the trade-off between the part goals in the objective function and that in phase two, after a significant improvement in overall energy costs, the optimization soon reaches a point where no significant improvement is achievable for any part goal, without creating solutions with unfinished products. Increasing the optimization step-size - – a measure to reduce the possible solution space size – from 1 seconds to 300 seconds improves both optimization speed and solution quality (see plot (c)).

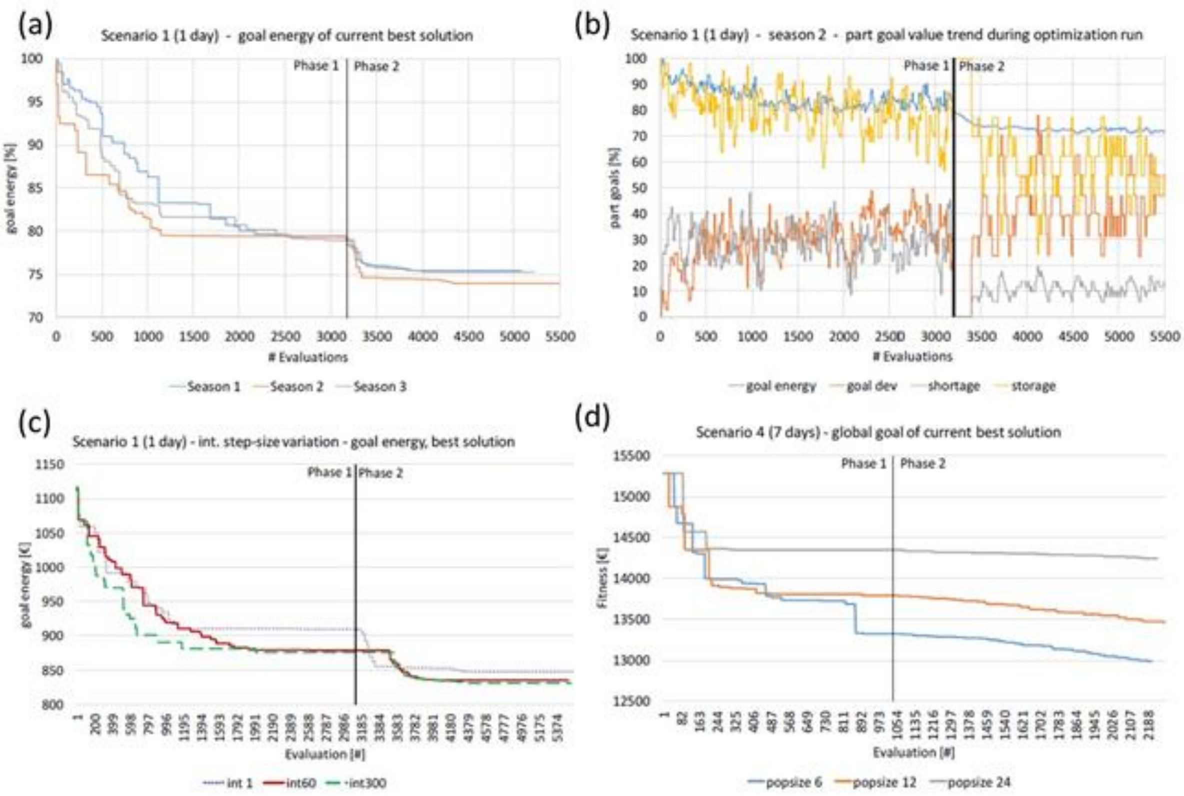


Figure 9: (a) energy goal trend of current best solution; (b) part goal trends of mean values per generation; (c) influence of varying optimization step sizes; (d) varying GA population sizes for 7-day scenario

The overall optimization, in terms of a reduction of the objective function value, in the one-day scenarios was around 50%. This includes lowering penalties for late deliveries, which are a common occurrence in the manual planning process. The energy consumption could be lowered by 33%, while the associated overall energy costs – including CO2 emission costs – dropped by 25%. The results could be obtained in ~4.400 simulation evaluations and as many intermediate solutions (with default settings). In the result trends, it is apparent that the number of evaluations to achieve good results could be reduced to ~2.300 evaluations by shifting the phase transition point to around 2.000 evaluations. On a standard intel-i7, 4 GHz processor 2.300 simulation evaluations take ~3 hours to execute. By further reducing the population size, the optimization speed can be significantly increased, however this also leads to less reliable results – one of the major advantages of population based metaheuristics is the simultaneous optimization of a large population of intermediate solutions (see plot (d)). With an further developed objective function, which considers the operating time of the core aggregate and the set-up time for a product change in production with a set-up cost matrix, similarly good results, like in the one-day scenario, could achieved in longer scenarios.

2.6 BaMa Prototypes

2.6.1 First Prototype (MOBA)

For an initial proof-of-concept demonstration of the simulation method, a simple example model was derived and implemented in MATLAB. In particular, the MatlabDEVS toolbox (developed by a team of the Hochschule Wismar) was chosen that provides a simulation engine based on Parallel DEVS and includes capabilities for hybrid discrete/continuous simulation.

The example schema is shown in Figure 10, a complete documentation can be found in the appendix. The model consists of a simplified version of a production line, including logistic equipment, a building with four thermal zones and building services with a heat, cold and an electric energy supply. The example was chosen in a way to represent all sub-classes and basic concepts in order to proof the feasibility of the formalism. Although the case study functions primarily as a proof of the formalism, due to the careful definition of the scope of the example it is used for the assessment of the complexity of the use case MPREIS, which again is the most complex case of the industrial partners. This way the entire BaMa methodology is put to test.

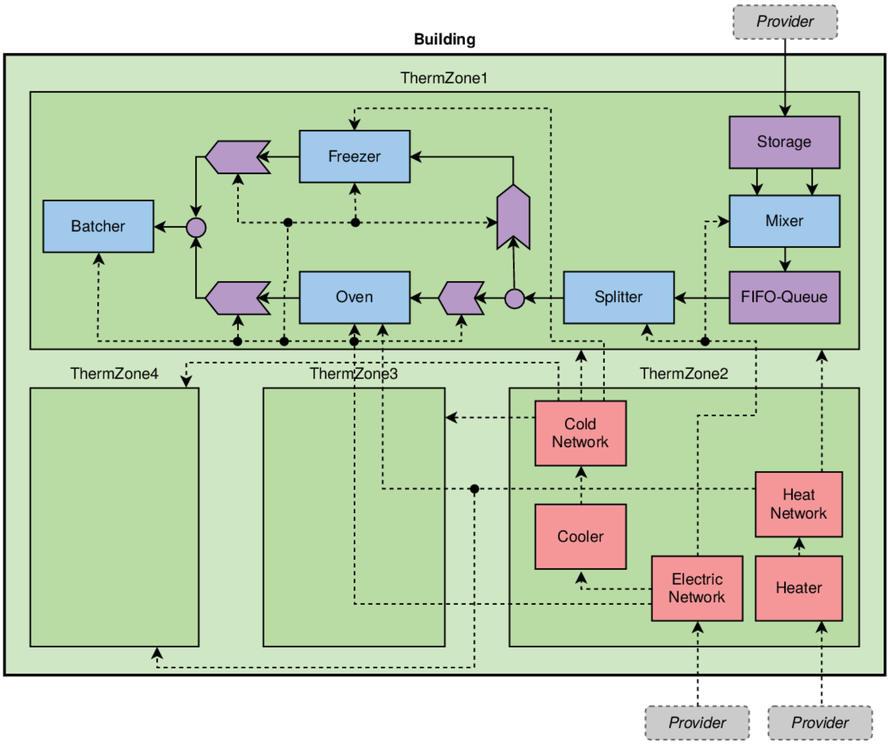


Figure 10: Model of the first prototype

The proof-of-concept implementation shows that the chosen formalism is suitable for the description of the different cube classes necessary to model a production plant. Important knowledge for the implementation of the entities in the discrete behaviour is gained. Another major finding is that, while third party software like MATLAB can be used for prototypical implementations, the shortcomings of using closed source simulation tools for modelling large-scale applications with the DEVS formalism are significant. Because the software does not natively support PDEVS simulation (but instead the engine is built on top of the MATLAB environment), certain workarounds are necessary. This not only affects the computational performance but also the process of implementing models. It was concluded that for the BaMa toolchain and a native integration into existing automation systems, it is best to implement a Parallel DEVS engine from the ground up.

The process of designing and examining a prototypical implementation was conducted in close collaboration between the research partners and AutomationX. The findings and conclusions resulted in the start of the development of the BaMa tool chain by AutomationX.

Partner AutomationX attempts a novel implementation of a hybrid simulation engine and deep integration into their software architecture, in order to incorporate this functionality with existing monitoring, data storage and visualization solutions.

AutomationX started with implementing a Parallel DEVS engine and support for continuous ODE solvers, followed by a re-implementation (in C++) of the first prototype example. This implementation could then be validated against the MATLAB implementation, with the results showing satisfying compliance.

2.6.2 Second Prototype (SEPPI)

To develop both the BaMa methodology and the use cases further, an advanced case study was chosen based on the production facility of MPREIS. The second prototype extends the first prototype and features a complete production line from start to finish, see Figure 11. The next paragraph gives an overview about the most important modelling details. A complete documentation of the model is given in the appendix.

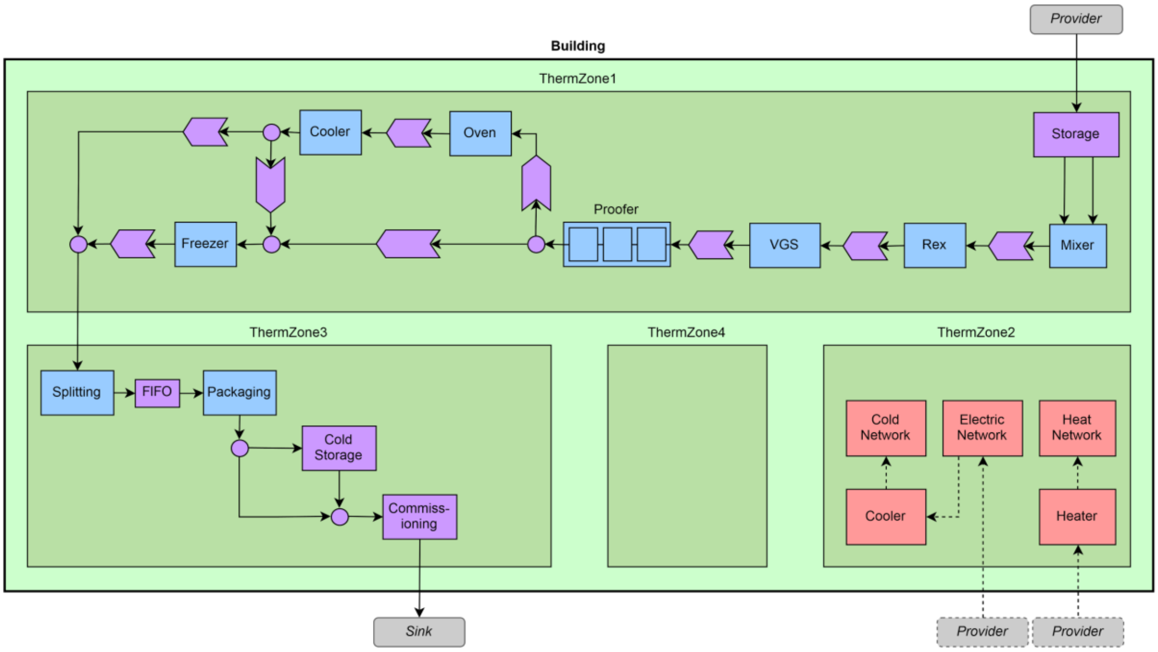


Figure 11: Model of the second prototype

The model of the second prototype (SEPPI) serves as enhancement and extension of the model of the first prototype (MOBA). The production line comprises three different material flows through the production featuring twelve products on the corresponding cube classes. The products differ in:

- Material flow and behaviour according their working plans through the production
- partial lead times on the corresponding aggregates
- Quantity structures and initial “barrel” quantity
- Hourly output-rate
- energetically behaviour

Within the logical process flow the simulations makes use of the following aggregates, represented by the following cube classes:

- Storage: simpleStorage

- Mixer: combining (merging)
- Conveyor belts: belt
- Rex: splitting
- Pre-Proofer: production unit
- Proofer: 3x production unit
- Heuft oven: oven
- Heuft cooler: oven
- Freezer: production unit
- Packaging: splitting + FIFO + combining (batching)
- Storage for frozen products: complexStorage
- Commissioning: complexStorage
- Electrical net: energienetz_OS
- Heating net: energienetz_MS
- Coolong net: energienetz_MS
- Heating: heizung (energy converter)
- Chiller: kaeltemaschine (energy converter)

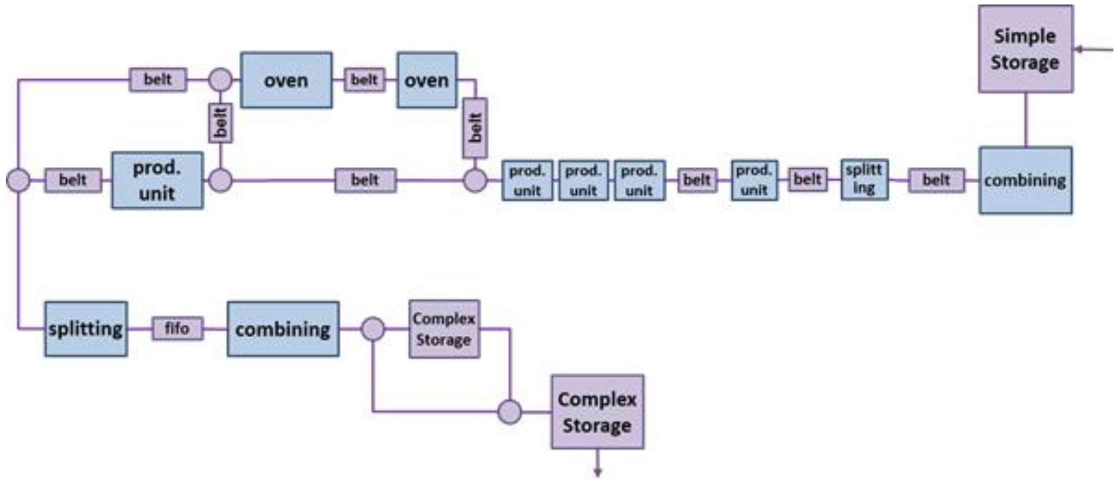


Figure 12: Cube classes within the production line (second prototype)

Figure 12 shows the used cube classes structured according their process sequence: The entities are generated at the “Simple Storage” starting their specific material flow through the production system. The entities themselves are represented by different objects at the corresponding stage of the production:

- Storage to Mixer: raw materials for a specific barrel
- Mixer to Rex: Barrel [kg]
- Rex to Packaging: A batch of pieces on a board → “Peelboard”

- Beyond Packaging: (tabular bags) → boxes→ (pallets); within simulation used: boxes)Table C7.1: Products of production line (MPreis)

Typ	Produkt	Kategorie
Type 1	Haussemmel_TK_HB	Half-Frozen
Type 2	Haussemmel	Fresh
Type 3	Haussemmel_TK	Frozen
Type 4	Baeckersemmel_5er	Fresh
Type 5	Baeckersemmel_10er	Fresh
Type 6	Baguette_TK_HB	Half-Frozen
Type 7	Mini_Baguette_TK_HB	Half-Frozen
Type 8	Dinkelweckerl_TK_HB	Half-Frozen
Type 9	Alpenkornweckerl_TK_HB	Half-Frozen
Type 10	Mini_Finnen_TK_HB	Half-Frozen
Type 11	Mohnsemmel_3er	Fresh
Type 12	Sesamsemmel_3er	Fresh

Figure 13: Used cube classes structured according their process sequence

Based on the implementation of the first prototype, AutomationX was able to implement the second prototype directly, without the need of an intermediate MATLAB implementation.

In contrast to the first prototype, the extended model was to be parameterized based on real-world data. For this, a series of measurements were carried out at MPREIS. From the data obtained, parameter values for the model could be derived.

2.6.3 Final Implementation

For the final and last prototype, the scope enlarges from one production line to four different production lines: One production line for rolls (as in the prototype before, line 3), one line for donuts (line 4), one line for special breads (line 2) and one line for large breads (line 1). The target function has to be adapted to cover this enlarged scope. The following target function serves as basis for the description of the lines 1,2 and 3 (because line 4 has only temporary up-times), thus the model will emphasize on the first three lines, before the 4th line (which has no interactions with the other lines) has to be considered.

$$f(x) = \sum_{j=1}^{j=m} \omega_1 f_1(d_j) + \sum_{i=1}^{i=n} \omega_2 f_2(c_i) + \omega_3 n_2 k_1 + \omega_4 n_3 + \omega_5 n_4 + \omega_6 n_5 + \omega_7 n_6 + \omega_8 n_7 + \omega_9 n_8 + \omega_{10} n_9 + \omega_{11} n_{10}$$

ω_1 delivery penalty weight

ω_2 storage cost weight

ω_3 energy cost weight

ω_4 quantity variance weight

ω_5 Heuft 1 oven uptime weight

ω_6	Vato oven uptime weight
ω_7	Stikken oven uptime weight
ω_8	Heuft 2 oven uptime weight
ω_9	setup cost L1 weight
ω_{10}	setup cost L1 weight
ω_{11}	setup cost L1 weight
n	total number of production lots
m	total number of product types
$f_1(d_j)$	evaluation function for delivery tardiness on production lot level [€]
$f_2(c_i)$	evaluation function for storage costs on production lot level [€]
$n_2 k_1$	total energy: costs and CO_2 in €
n_3	total (quantity) output: SOLL – IST
m	quantity of different product types within the BaMa simulation
n	quantity of production lots within the BaMa simulation
n_4	oven-uptime L1/2 Heuft (time) in €
n_5	oven-uptime L1/2 Vato (time) in €
n_6	oven-uptime L1/2 Stikken (time) in €
n_7	oven-uptime L3 Heuft (time) in €
n_8	setup-costs L1 in €
n_9	setup-costs L2 in €
n_{10}	setup-costs L3 in €

The recommended weights for the listed target function including the individual part-goal weights above as following:

ω_1	ω_2	ω_3	ω_4	ω_5	ω_6	ω_7	ω_8	ω_9	ω_{10}	ω_{11}
1	0.1	2	1000	1	1	1	1	10	11	12

Within the scope of the final prototype, the corresponding oven-uptimes and oven setup-times have to be evaluated separately with individual weights.

Storage costs (according to $f_2(x)$) have to be evaluated on production lot level, while costs for delivery tardiness (according to $f_1(x)$) are evaluated on product type level. This enables a different consideration for production lots, that are to be stored and, on the other side, delivery penalties (on product-type level) Delivery penalties are calculated on basis of missing quantities from a defined product-type at a certain period. This reflects the planning behaviour and fits best to the reality at the use-case-partner MPreis and that is why this has been accomplished this way.

The following adaptations have to be implemented into the final prototype:

- Delivery penalties to be realized with 20€ (per pallet frozen products) and 100€ (per pallet fresh products)
- Doubled storage costs for frozen products to justify the high acquisition costs of the expanded frozen storage
- Virtual operating costs of the oven aggregates of production lines 1 - 3:
    - Heuft L1/L2: 100€/operating hour
    - Vato L1/L2: 150€/operating hour
    - Stikken L1/L2: 200€/operating hour
    - Heuft L3: 100€ / operating hour
- Virtual setup-cost matrix of the oven aggregates of production lines 1 - 3 (in € per setup process, has to be defined with MPreis)

The final prototype has not been fully implemented yet. Further testing has to be performed by AutomationX, who is ultimately planning to deploy this prototype (in a customized variation) at MPreis.

The AutomationX aX5 has a modular structure. It contains modules to enable visualization, PLC programming compliant with IEC 61131-3, and different data management modules, as well as a wide range of interfaces and communication protocols. These are communicating via the AutomationX Framework. The BaMa-Tool should therefore be used in the same way for data exchange.

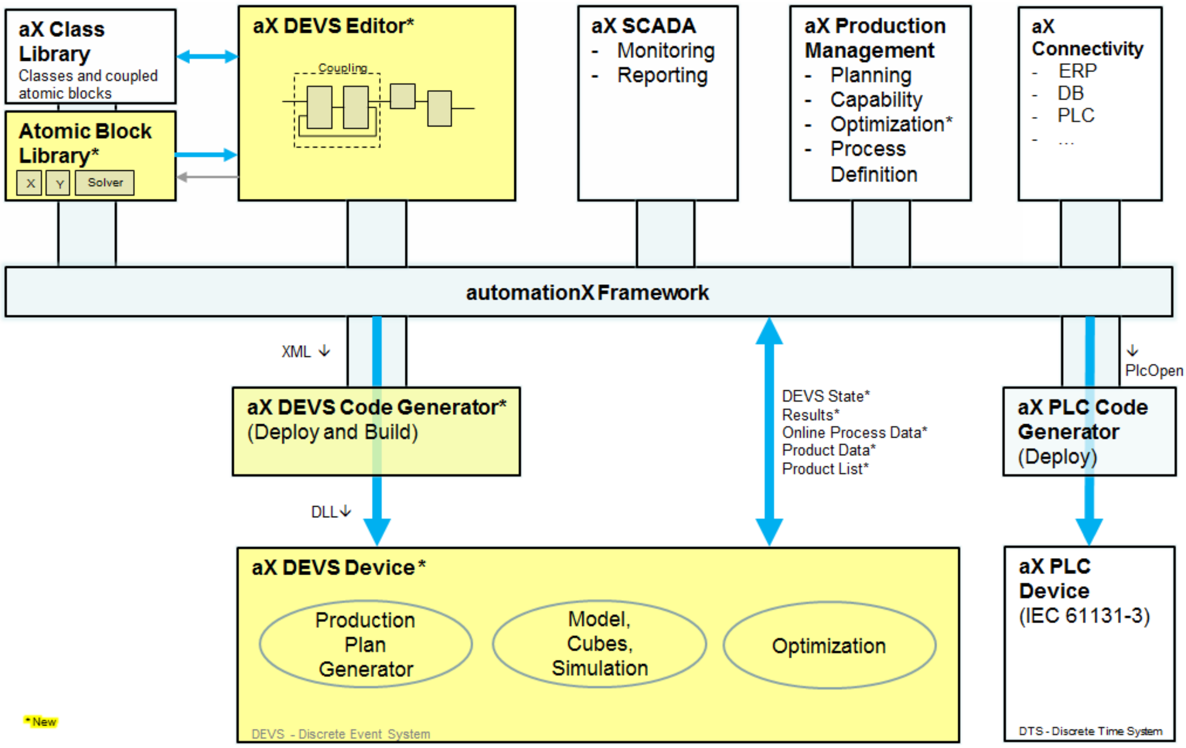


Figure 14 AX Framework

In Figure 14 the schematic layout of the BaMa-Tool implementation is shown. The yellow boxes are the new developed parts for the BaMa-Tool, whilst the white boxes show the already existing functionality.

The aX DEVS editor is used to connect the different types of cubes together to represent the real layout of the production line for the simulation. The atomic block library contains a set of different cubes. After the coupling of the cubes in the editor, a code generator will build and compile the drawn connections, including the cubes, in programming code to a file. This file receives the input parameters as product data, optimization parameters and the product list over framework and delivers simulation data and the optimized result for the production queue after execution. The product data, product list and parameters are placed in the database. The operator, planner or consultant can maintain this data over the aX SCADA visualization, which provides a comfortable interface to the database.

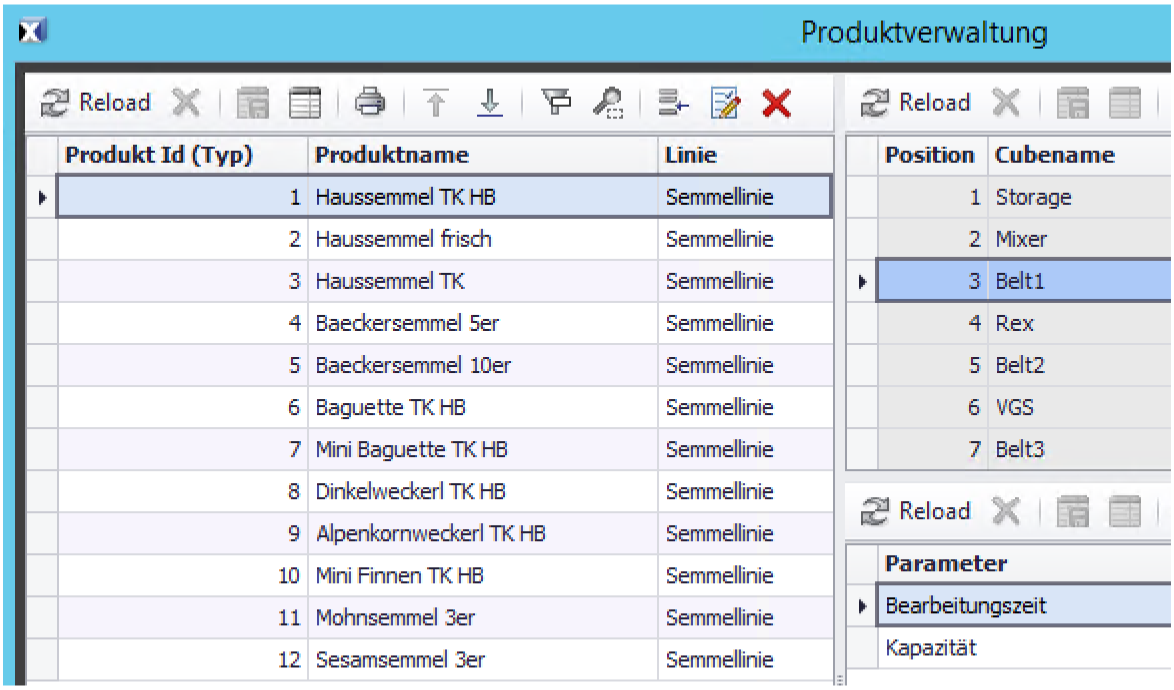


Figure 15 Product overview

Figure 15 shows the form where the product data can be maintained. The responsible person can add, delete and modify products. The product list is presented in a similar way. The optimized production queue can be transferred over an interface to an existing ERP system. Furthermore, the queue can be exported to a datasheet or printed.

Produktionsplan Semmelline (Linie 3)

Eingangslager			Ofen	
Produkt	Teige	Startzeit	Temperatur ändern	Ofen Sollwert
Sesamsemmel 3er	9	20.09.2017 00:00	20.09.2017 01:57	225,0 °C
Haussemmel TK	11	20.09.2017 01:39	20.09.2017 04:37	160,0 °C

Figure 16 Example production plan

Figure 16 shows an optimized production queue sample for one production line with the following values: starting time, time for temperature change of the oven and target temperature. Figure 17 gives an example of simulation data. It shows the simulated temperature of the oven during the whole production process. The y-axis is covered to protect the costumer’s technology.

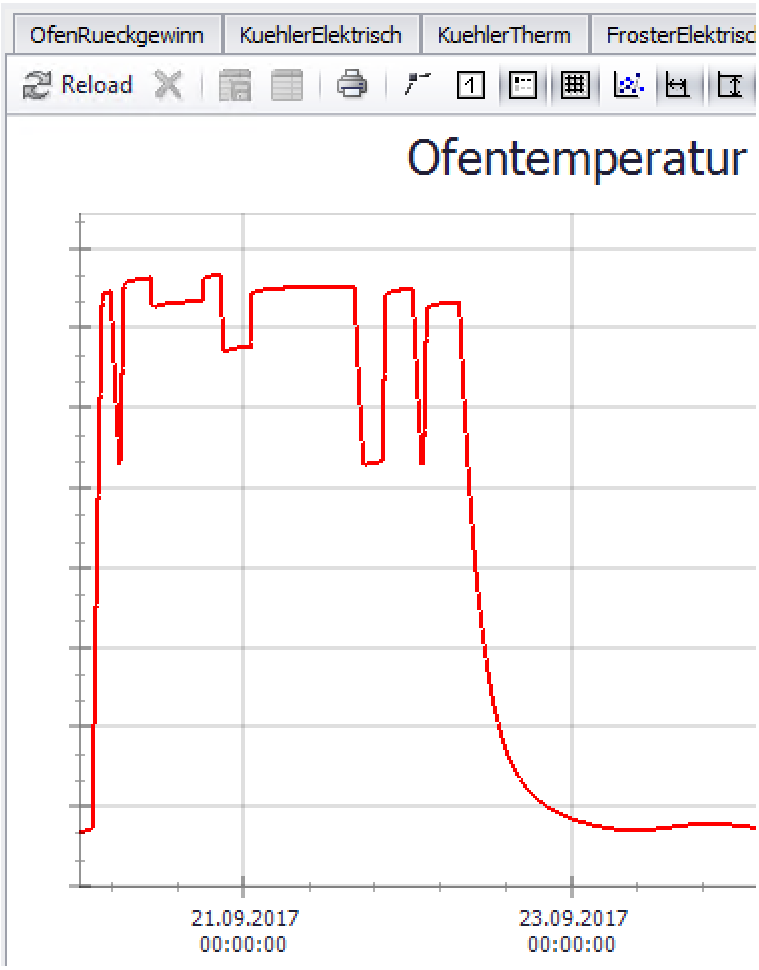


Figure 17 Simulation result: Oven temperature

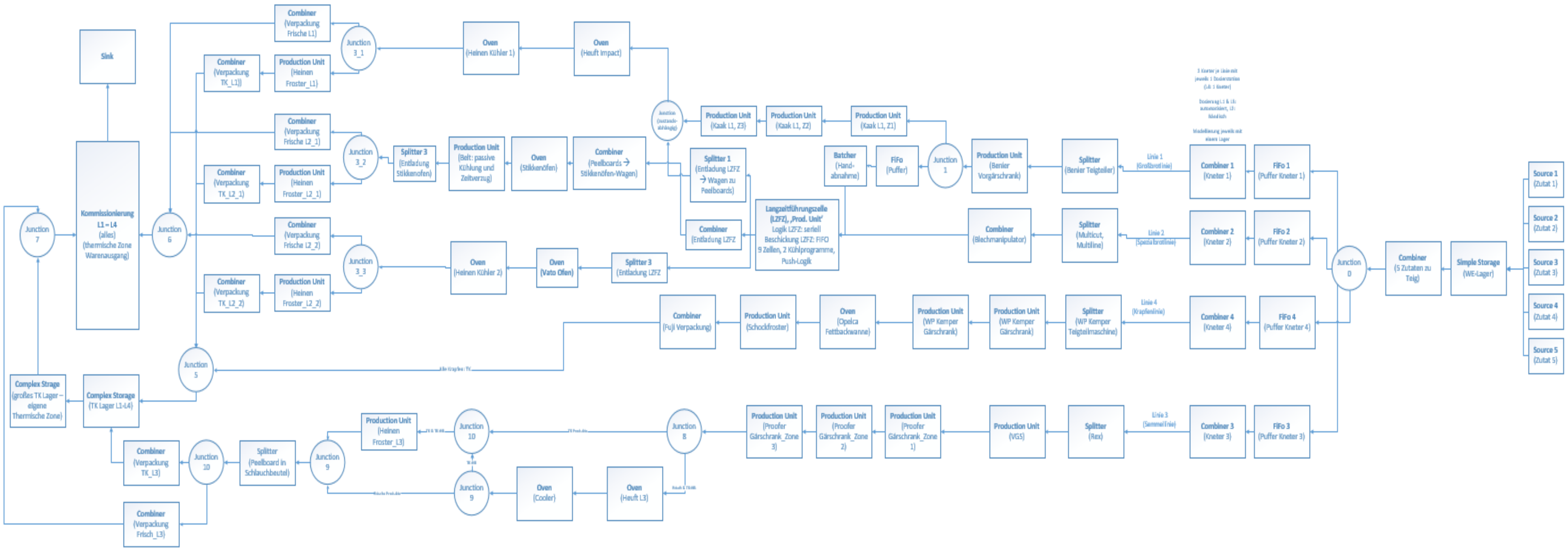


Figure 18 Overview final prototype

2.7 Experimental Cube

In order to be able to develop the solutions intended in the project as fast as possible while still having the possibility to continuously receive feedback from partners and industrial companies from outside the project consortium, an experimental cube was set up.

This experimental cube was physically located in the TU Wien laboratory, which is by now known as “Pilotfactory Industrie 4.0” in Aspern. In the following section, the main elements of this experimental cube will be described in more detail.

2.7.1 Sensors and Communication Protocols

There, three production machines where equipped with sensors in order to derive the energy flows through the shop floor. Those sensors involved electrical energy sensors, but also flow sensor for the measurement of pressurized air.

In order to be able to be able to process the data generated by the sensory, a network interface had to be established. After experimenting with many different protocols, a MODBUS based solution was implemented in the experimental cube. Currently, a OPC UA- based solution is under investigation and will be implemented in the future.

2.7.2 Database and Data Aggregation

Any data generated by sensors needs to be stored in a database. This database had to be defined in order to meet the requirements of different partners as well as being specific enough to be useful. A main criterion for the system architecture was to emulate environmental conditions as close as possible to existing IT landscapes currently found in the industry.

Therefore, a relational database was chosen as a basic building block for the desired application. PostgreSQL[2] is an open source solution. Furthermore, its reliability and capability has been proven in many applications similar to the one at hand

The ER diagram depicted below shows the abstract design of the underlying database. For any object of interest, which can be a machine component, a building or some other cube, sensors can be deployed. Each sensor in turn records an arbitrary number of data points.

Using the composite primary keys start and end, the same sensor can be deployed to different objects of interest in consecutive periods.

[2] https://www.postgresql.org/

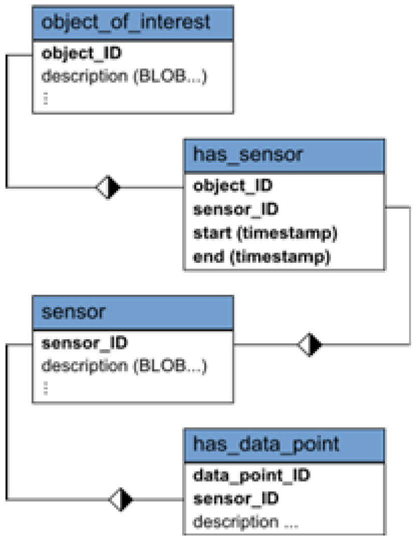


Fig. 1 ER Diagram

Figure: 19 Database schema

Due to the schema of the database, any reading or writing operation of sensory data can be done using only the primary keys shown in Figure: 19. Other information concerning objects, sensors or data points is not needed for those operations.

All recorded sensory data is time series data and the required tables for storing it are not depicted in Figure: 19. The structure of these tables however is easily described. Each distinct sensor_ID corresponds with a table name. Within these tables, for every data_point_ID, a related column name is used.

The primary key of each of these tables is the timestamp. Usually, for each timestamp, one value is recorded. The system however allows for an arbitrary number of values (different data_point_ID's) that can be stored in connection with one timestamp (i.e. CNC- system data).

Allocating exactly one table to each sensor facilitates simultaneous read or write operations from various devices. Furthermore, because of this structure, the records in each table are sorted by their timestamp and can be expected to have approximately constant sampling rates.

The separation of data tables from the allocation tables depicted in Figure: 19 also makes it possible to operate several, distributed data storages. Those can then be accessed via one centrally stored database containing all the necessary URI's and the deployment timestamps.

Monitoring and Visualization

For the machines included in the experimental cube, the relevant energy data was stored in a database. This database was consequently used as the backend of web-based a visualization solution. Using this solution, energy data could be monitored live via any browser.

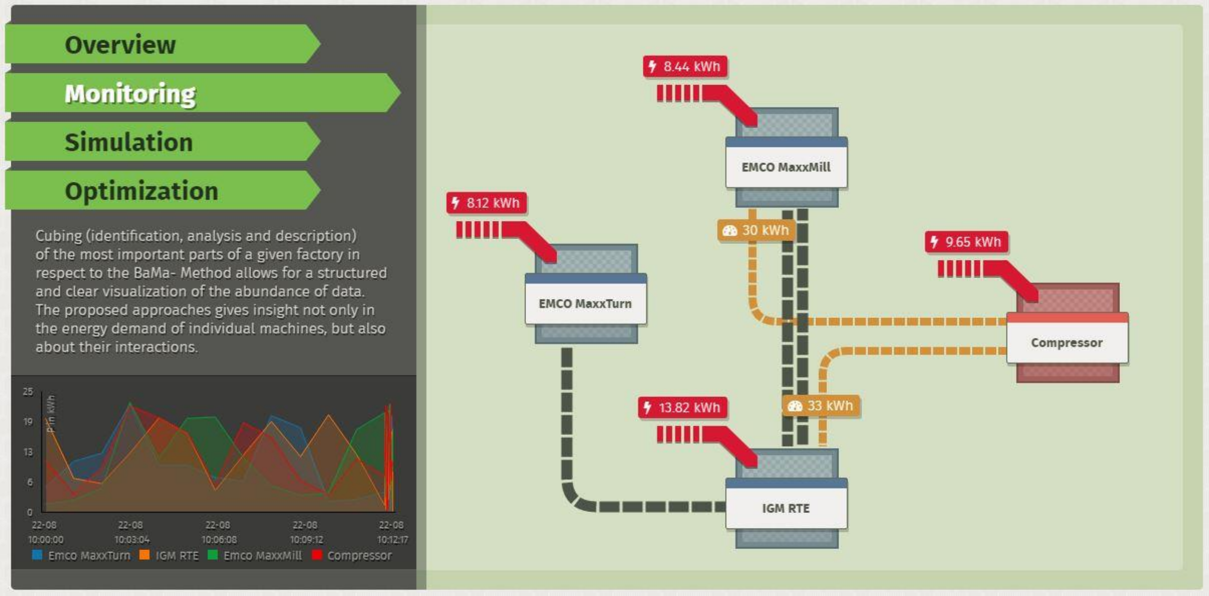


Figure 20 Experimental Cube Monitoring

The implemented monitoring solution does not only show the instantaneous power demand per machine, but can also be used to view historical data and the gives information about the semantic meaning of the respective flows (i.e. where does the energy come from, where does it go).

2.7.3 Simulation and Prediction

In regards to the simulation, an extended model of the physical shop floor was implemented. Both, continuous (energy-related) and discrete (material-related) elements can be simulated, as the implemented simulation framework uses the DEVS/DESS formalism. The implemented cubes are based on the cube descriptions provided together with this document. The function of this prototype showed the research team, that the chosen formalism is feasible and can be implemented.

Apart from the production machines, also a model representing an energy system was implemented. Based on the current boundary conditions, this system works more or less efficiently, which in turn changes the simulation results.

The resulting simulation model was then used, to add a functionality to the web- based tool. In order to illustrate idea of simulation in the context of the BaMa project, a simplified production-planning scenario was created. Using the simulation model, the user can schedule given customer orders to the available machines. By starting the simulation, the user then receives information regarding the cumulative energy demand of his plan and the resulting time delay. Based on this information, he or she then can adapt the plan and evaluate the improvements (or deterioration) of the results. It is understood, that the presented results only are a small subset of the available results, which come out of the simulation runs. This was deliberately chosen this way in order to not overwhelm the users and reduce the amount of information to the necessary minimum.

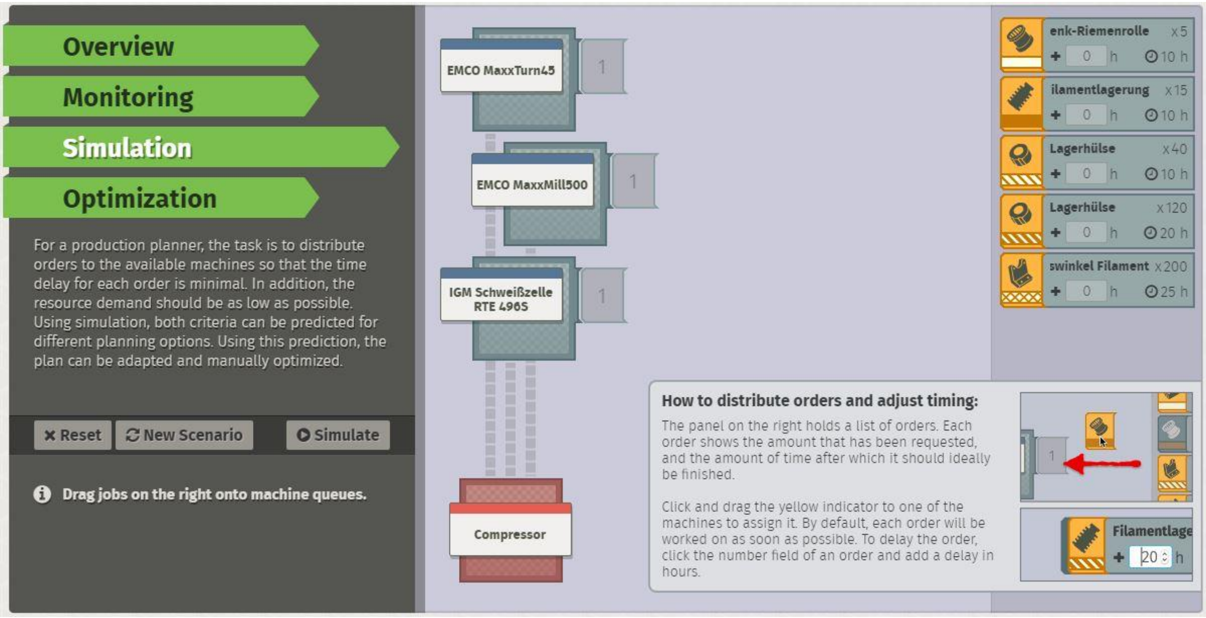


Figure 21 Experimental Cube Simulation

2.7.4 Optimization and Improvement

The optimization algorithm was implemented using Python. Based on the findings of the research project, a genetic algorithm was chosen to solve the optimization tasks. In the target function, the only two visible simulation results (time- delay and energy demand) where included. Based on a user input, the weights between those two parts can be adjusted which results in different solutions. Just as the first two modules, also for the optimization module a web- based frontend was developed.

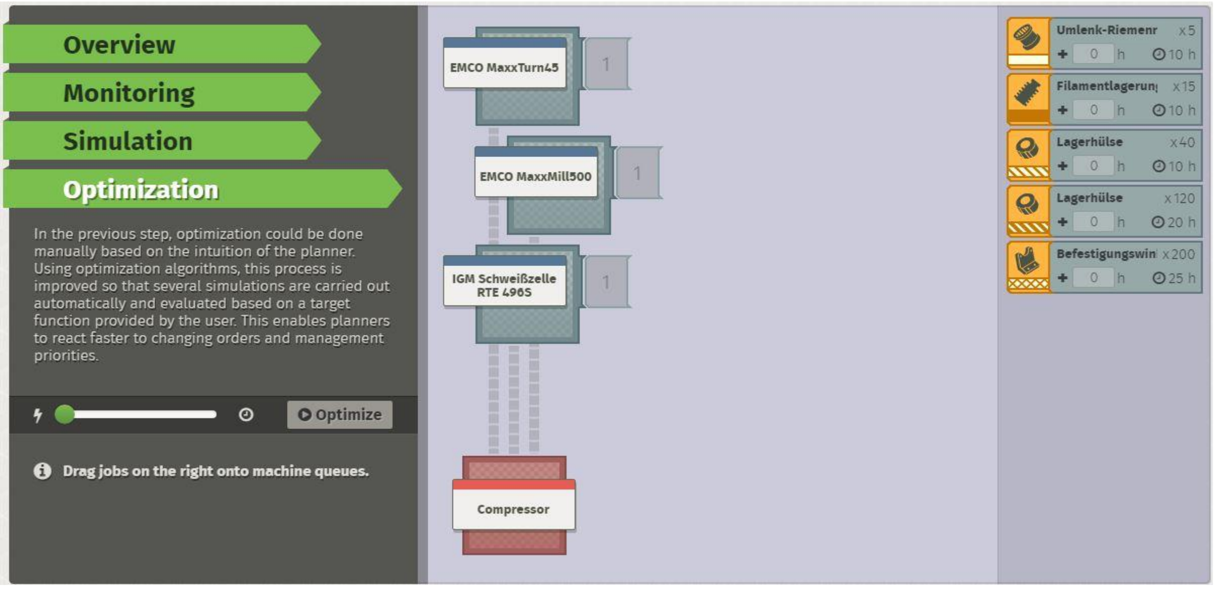


Figure 22 Experimental Cube Optimization

Already in the simulation part, it was possible to change the results per run by adjusting the production plan. Based on the individual goals, the user can for example try to minimize the time delay to a minimum. Due to the simple nature of the presented problem, this would be possible by just adjusting the scheduled production times accordingly. A bit more complicated would be the task to minimize the energy demand of a given set of orders. The user does not see the energy demand in advance and is not able to anticipate or understand the mechanisms, which result in the overall energy demand. In this respect, the web- application is just like reality.

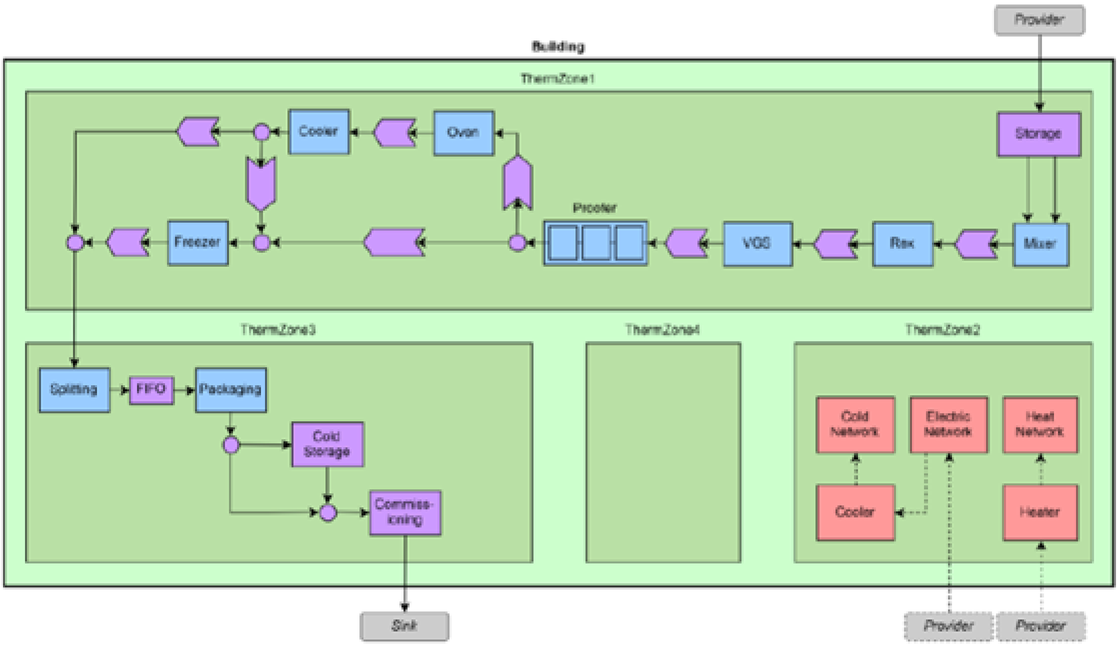
With a given scenario from the simulation part, the user can decide to enter the optimization process. Here, the scheduling cannot be done manually anymore. The only point, where the user can interact with the system is a scroll bar, where the parametrization of the target function can be adjusted. By changing the position on this scroll bar, the user can decide whether time-delay or overall energy demand should be the target of the optimization process.

2.8 Use Cases

2.8.1 MPreis

For this Case Study, the simulation of an actual production line for rolls in an industrial bakery plant was chosen as the production system. It consists of nine major production machines, nine conveyor belts with junctions and two storage components within the production logistics system. The products, baked and deep-frozen rolls, use different material flow variants – mainly with and without passing through an industrial oven – and require different process parameters, e.g. temperatures and processing times on machines. These product characteristics are stored on and used as input via process sheets. Two of the production machines – an industrial oven and a freezer – feature a distinct thermal-physical behaviour. The basic model structure is depicted in Figure 23.

In the Technical Building Services (TBS) and energy system, there is a heater providing heat via a heat network to the industrial oven and the different halls/subsections of the factory building. Next to the heat network, there are three cold networks and one electric network. The



cold networks contain five chillers. The external environment is considered by importing

Figure 23 Simulation model: structure plus material and energy flows

weather data – i.e. temperature, wind and cloud coverage. Scenarios for three seasons in 2016 have been tested (seasons following the weeks 03/34/44). In the simulation model, the building itself is divided into four thermal zones, representing the main production hall, a room with technical building services equipment, an office building and a freezer warehouse – each of those zones is supplied with heat/cold and exchange heat with each other during the simulation. The hybrid simulation is implemented in a C++ software and the optimization is implemented in Matlab® using the Global Optimization Toolbox. The simulation model was parameterized with actual data from production, process and comprehensive energy measurements conducted in the production plant.

The production scenarios 1-day-/7-day-/30-day-scenarios (simulated time) feature all twelve product types that are produced on the production line. The imported production/demand schedules are actual production schedules from the fall of 2016. The base planning is the actual production schedule created by manual planners that was executed in the past against which the optimization results are now being evaluated.

With an further developed objective function, which considers the oven-operating time and the set-up time for a product change in production, similarly good results, like in the one-day scenario, could achieved here in longer scenarios.

For the chiller network a sub-optimization (phase 3) is included, to optimize energy-consumption in more detail. This further increases the overall optimization potential and introduce more complexity for the optimization task

The next iteration of a simulation prototype for MPreis will contain the complete model of the production line (4 lines).

2.8.2 Infineon

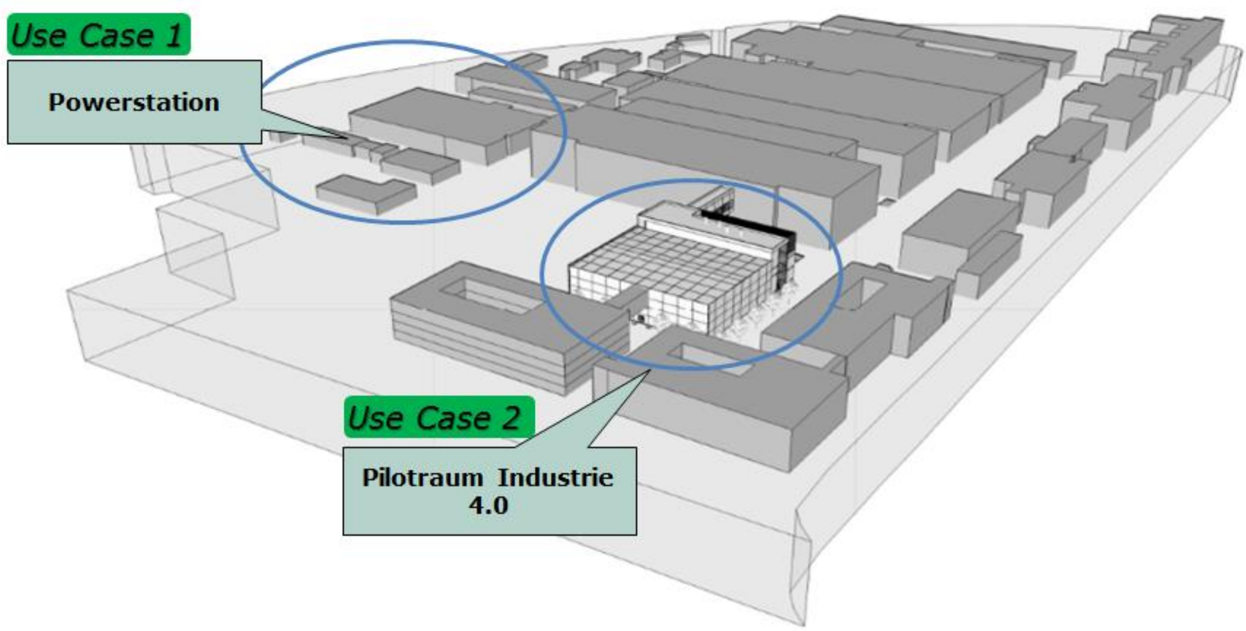


Figure 24 Infineon Use Cases overview

Regarding the Use Cases, the concrete goals were revised based on the preliminary project findings. The following goals where the basis for the last project year:

Use Case 1 (Powerstation):

The final scope of this Use Case was formulated as follows: The current operating strategy is to be adapted so that the operating hours are no longer used as sole decision criterion. Rather, the energy efficiency of the overall system energy center should be at the center of decision-making. Depending on the current weather data, the required cooling capacity, and the heat demand, the best system wiring should be determined. Determined operating configurations are communicated to a human operator in the form of a recommended action. After a review, these recommendations can be passed as control signals to the machines.

Use Case 2 (Pilotraum Industrie 4.0):

The production-specific energy efficiency should be improved. Current weather data or weather forecasts, as well as information about the current system utilization should make it possible to predict the energy and media requirements. The production plan is to be regarded as a guideline and not as a degree of freedom. For this purpose, a correlation between implanter utilization and total energy consumption of the building should be found.

The prediction is to form the basis for a comprehensive system, whereby the operation of the energy center can be controlled depending on the expected utilization of the systems of the production and building systems.

Regarding the implementation of Use Case 1, Amesim, a simulation environment for continuous phenomena was chosen. The simulation models developed by TU Vienna (Figure 25) where implemented in order to reflect the status of the system in operation. The running Simulation was then connected with the existing SCADA System currently in operation at Infineon in order to be able to use monitoring data directly for scenario generation. Based on changeable scenarios, composed of weather conditions as well as demanded cooling and heating power, the cost for the power generation was simulated along with specific KPIs regarding for example the even load of the chillers.

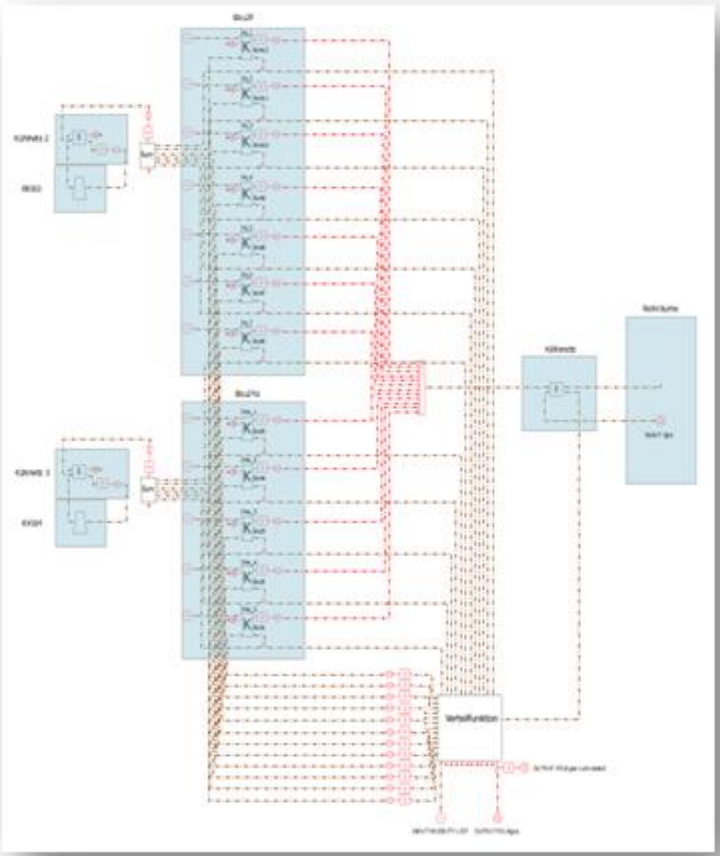


Figure 25 Infineon Use Case 1 Schema

In the final step, an optimization schema was defined in order to find the optimal operation strategy. To define this optimum, a configurable target function was implemented. This allows the user to adapt the target function in order to reflect changing priorities. Based on the conducted experiments, the expected saving potential for the optimization of the operation of the chillers lies in the range of 10-20% of the total electrical energy demand, which would be equivalent to 20 MWh per day.

In order to fulfil the requirements of Use Case 2, a simulation model reflecting the production plant under consideration had to be implemented. After the necessary details where clarified, a model reflecting both the building hull, six thermal zones and the HVAC system was defined and then implemented in MATLAB. In order to be usable for the responsible personnel at Infineon, a GUI was also developed (Figure 26).

After the validation process was over, final adjustments in the model had to be applied in order for it to produce realistic results. Then, simulation studies were carried out which led to valuable insights into the capacity limits of the system in place as well as the expectable energy demand based on weather predictions and production machine workload.

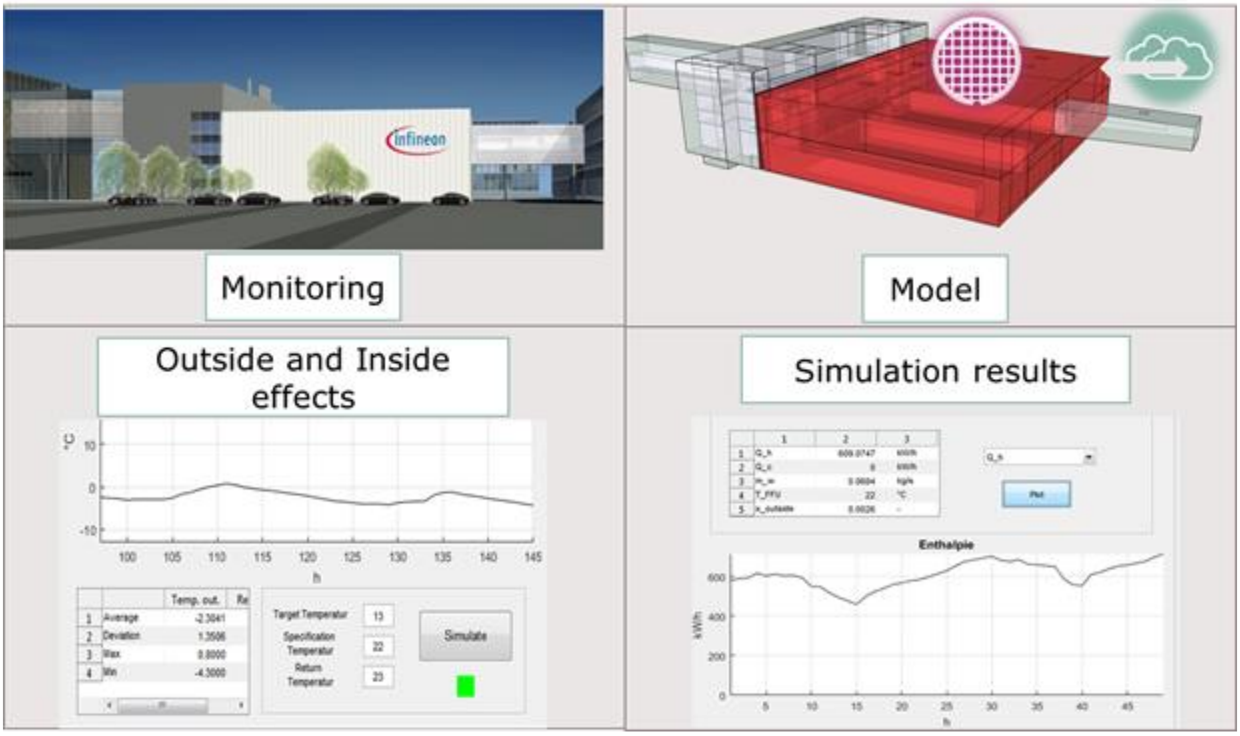


Figure 26 Infineon Use Case 2 GUI

2.8.3 Berndorf Band

Berndorf Band is a company operating in the production of transportation and processing belts made of carbon steel, stainless steel or titanium. The use case for Berndorf Band focused on the main production building, built in different construction phases, with the older part dating in the 1920s. At the start of BaMa project, the company's automation status did not facilitate the application of the whole BaMa methodology, since there was no general integrated system for acquiring production process data about machines' operation or HVAC systems usage. Therefore, priority was given to the implementation of the Monitoring module of BaMa and validation of the whole system through the cubes logic. The Berndorf Band use case consists on one hand from the evaluation of the planned and realized thermal refurbishment of the building in terms of indoor climate and on the other from the installation of a monitoring system on the production level.

The thermal refurbishment focused mainly on the roof over the older part of the hall, measuring a surface of 11,000 m², either by a new structural and roof skin construction or by addition of thermal insulation on the existing roof construction (Figure 27). Furthermore, a replacement of existing fluorescent electrical lighting with LED resulted in a reduction of connected load greater than 45%. Simulation models provided insight to the performance of renovations variants, incorporating operating patterns of production equipment and electrical lighting, derived from in-situ measurements [36]. Indoor climate condition characteristics were collected before and after the refurbishment. At the first stage, acquired data were used for validating the building thermal simulation models of the existing building. The analysis of the initial state showed, that the old part of the main production hall was more sensitive to outdoor weather conditions then the other buildings. During summer there were numerous hours where overheating was recorded. Upon this fact, the feasibility of passive measures to tackle such conditions in summer was analysed [37].

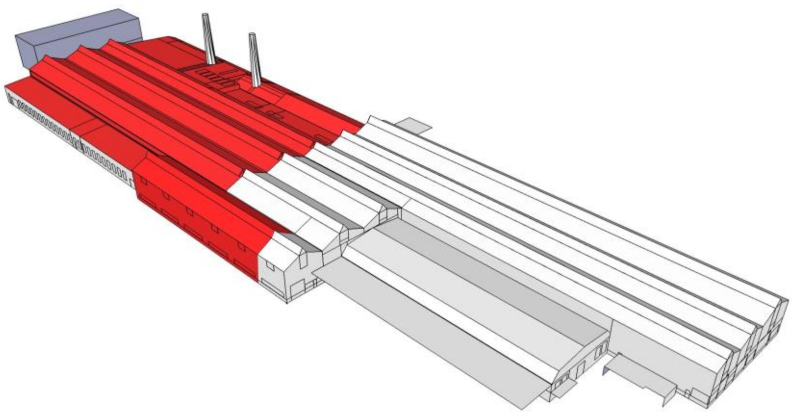


Figure 27 3D view of the main manufacturing hall, highlighted in red is the thermal refurbishment area

After the completion of the construction works in 2016, changes regarding thermal comfort of personnel in the hall before and after renovation measures were assessed based on questionnaires, indoor climate measurements and dynamic building performance simulation models. Results showed that indoor climate has been improved as temperature fluctuations were significantly decreased and the number of overheating hours during free running mode with natural ventilation in summer were diminished to zero for temperatures over 30°C, where those over 26°C reduced by 3% to 8.7% of the annual working hours (Figure 28). Assessing the qualitative criteria form the questionnaires showed that 70% of the employees believe that generally, the refurbishment measures have a positive impact on their thermal comfort, 21% do not spot a difference and only 7% are of the opposite opinion. Thermal comfort improved both during the winter and summer months, with 83% of the employees agreeing that long periods of overheating in summer have a negative effect on their productivity.

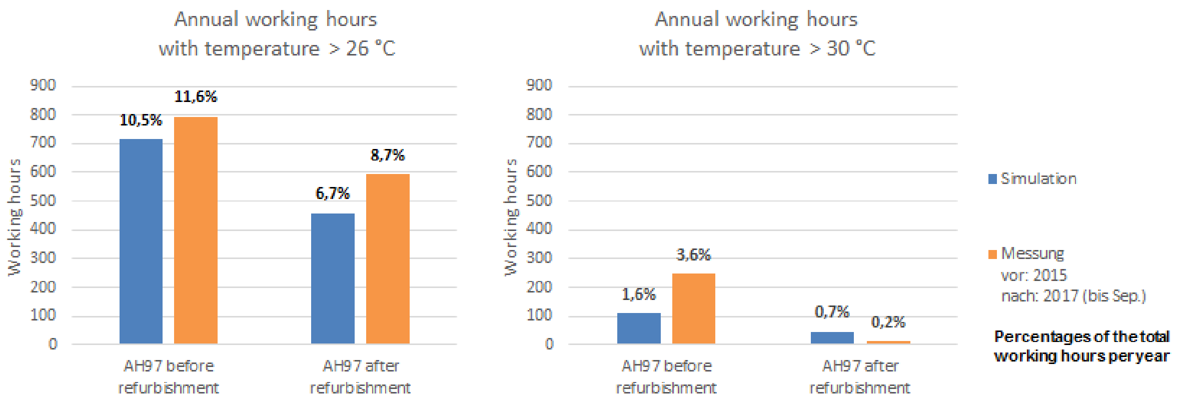


Figure 28 Comparison of the measurement and simulation results for the older part of the manufacturing hall (measuring point AH97) before and after refurbishment.

Additionally an investigation about the effect large heat sources was conducted, primarily focused on the annealing furnace. The 10 tons steel furnace, used on a daily basis to heat up cylinder of metal belts weighing 10 tons to temperatures over 500°C, has no exhaust system and the emitted heat stays in the hall. Simulation of different production patterns showed that at its current state the furnace heats up the temperature of an area in the hall measuring ca. 6,800 m² with a volume of 83,000 m³ from 0.5 to 1.5°C. During the summer period, there is an average increase of the temperature by 1°C when no additional natural ventilation through windows and skylight is provided. Taking into account the size of the examined hall, there is a significant amount of energy lost as waste heat and an exhaust system with heat recovery would have a significant potential for optimizing both the thermal conditions of the hall and the energy demand of the production line.

Complying with the energy efficiency regulation and in order to conduct a complete energy audit, Berndorf Band defined permanent electrical power measuring points on 3 hierarchy levels with 34 measuring points distributed along production machinery, compressors, office areas and supply power transformers. These were added to the existing ISO 14001 management system. Hence, main energy consumers were identified and initial assumptions regarding the importance of individual units were partially refuted. With the aid of the network diagnosis functions, the necessity of activating the reactive power compensation could be demonstrated. Therefore, the company is now able to acquire a transparent overview of the energy flows of the production processes and further implement the BaMa toolkit for identifying optimization potentials.

2.8.4 GW St. Pölten

In a first instance, Daubner Consulting conducted some energetic measurements of the chiller system and the compressed air consumption in order provide some basic information for the modelling of the main consumers. On basis of these first results, the additional measurements were planned.

Based on the findings of this preliminary analysis, a software tool aiming at increasing energy efficiency in industrial plants was implemented and tested by AutomationX. Thereby, measurable savings where achieved for GW St. Pölten.

Specifically, measuring instruments, which measure the current feed-in power, drive power and compressed air consumption were installed on three machines (EMCO T45, EMCO VMC600 and Chiron FZ15W). As part of the BaMa project, a monitoring software was developed for the mentioned machines, which displays the recorded data graphically, as well as evaluating them.

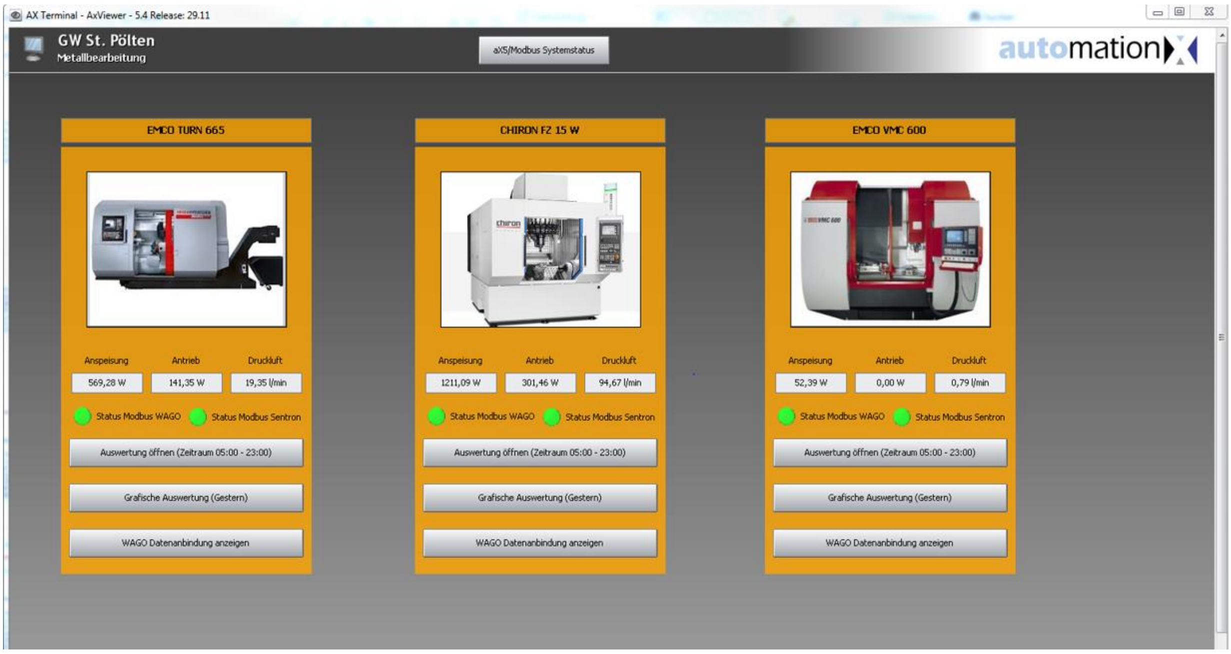


Figure 29 AX Dashboard for GW

The system is designed in such a way that it can easily be extended to also include other machines in the company. Therefore, only the required parameters need to be calculated using monitoring data.

As part of the data analysis, a number of organizational restructurings were completed, which significantly increased machine utilization and manufacturing efficiency.

Before the start of the project, the individual and series production was not spatially separated and both production types were carried out on all machines at the same time. In addition, there were high downtimes because programming happened directly at the machines. At the same time, series production was frequently interrupted in order to make last minute high-priority orders possible.

Based on the recorded data from a period of eleven days, a procedure was developed to monitor the current state of the monitored machine in real time. For this purpose, a k-means clustering algorithm was applied individually to every single measurement signal. Among other results, this analysis yielded the cluster centroids, which were used to quantify and categorize the measurement signal. In this use case, three clusters (switched off, stand by or production) where selected. As a result, the machine model calculated the operating status of the assigned machine at any time step using the measured signals per machine. Based on this, the utilization of the machine can be viewed and compared with the help of the monitoring software.

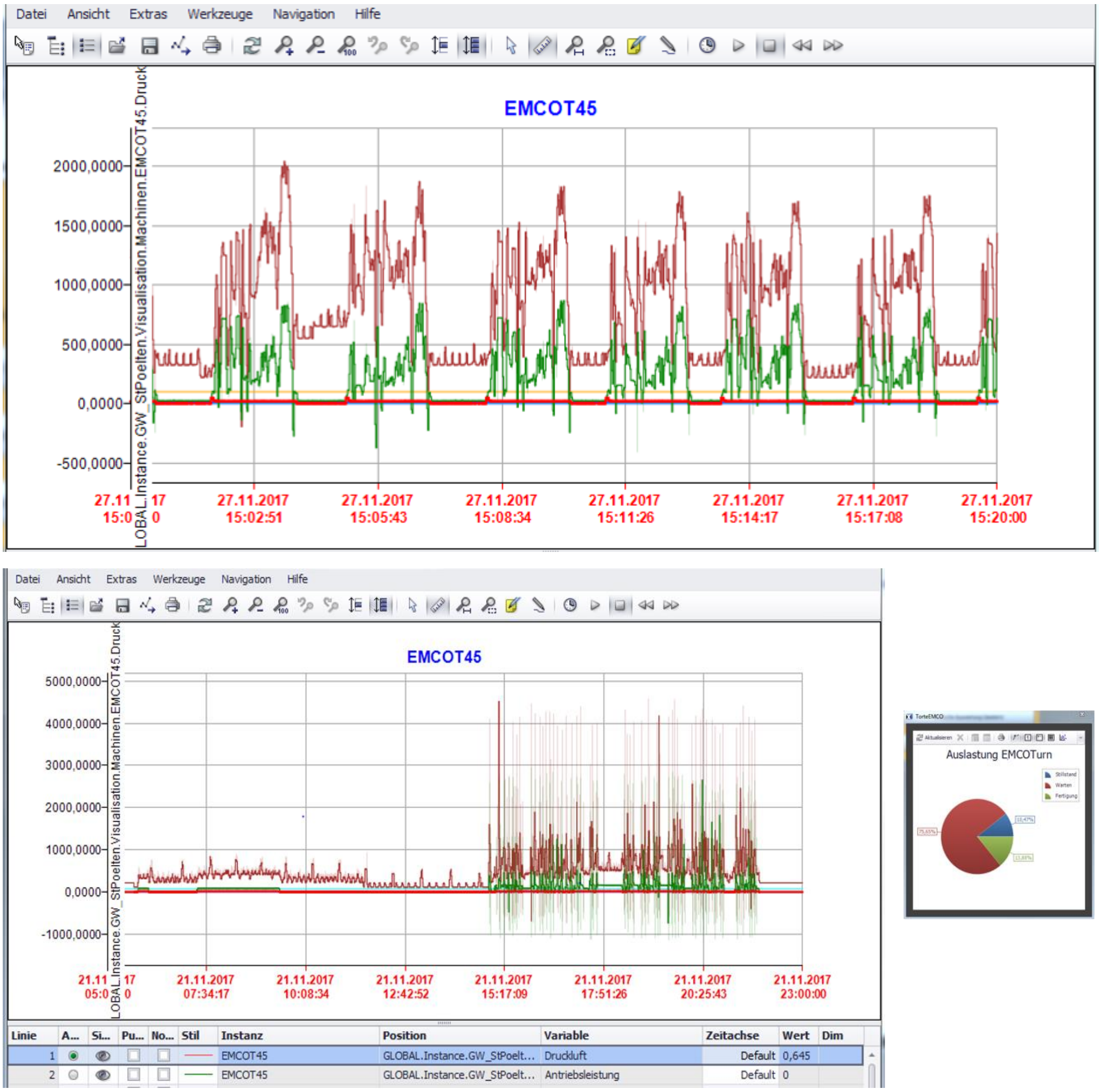


Figure 30 Power data analysis graph

By this evaluation, a restructuring was undertaken to increase the efficiency of the production.

The series and individual production was spatially separated, with the aim of increasing efficiency. In serial production, the programming and setup process was revised to do it external and not on the machine anymore if possible to achieve more time for production. Interruption due to individual parts are therefore no longer possible. Personnel changes were made in the individual production, which now exclusive employs skilled workers in this area. As a result, there is always sufficient capacity for individual parts, which often leads to series production orders.

By comparing the setup and programming process, the comparison of the monitoring analysis shows an increase in the manufacturing efficiency of 15% and with external equipment alone an increase of 4%.

Due to time-delayed starting of the machines, the peak power, which is relevant for the electricity price, could be reduced by 15%. Shutting down the cooling of the chilled water at the weekend resulted in further 20% energy savings. It is also planned to renew parts of the compressor technology, which will lead to energy savings of about 30%. By adapting storage space management, the travel and search times could be reduced by 5%.

The monitoring system also shows the fact that at night the machines are often not completely shut down, that means stand by instead of switched off which generates unnecessary energy consumption. In addition, if work on the machine, other than production e.g. programming is performed non-required units (cooling and control electronics) remain switched on. At this point, it is still necessary to work on raising awareness within the staff in the future to reach further energy savings.

2.8.5 Franz Haas Waffelmaschinen

The project partner FHW Franz Haas Waffelmaschinen GmbH aims at increasing the energy efficiency of the wafer lines produced by them, while at the same time maintaining the product quality of the baked goods. Special focus lies on the baking ovens as part of the wafer lines as they are responsible for a majority of the energy consumption.

In contrast to other use cases, the goal is not to use the BaMa tool for their own production at FHW, but to increase energy efficiency at their customer's plants by

- Monitoring: Reduce the energy demand of the production equipment such as ovens and coolers by investigating and analysing measurement data.
- Simulation: Optimize operation of the wafer lines via simulation-based evaluation of different production scenarios.

Monitoring:

The goal is to gain insights into the construction of more energy-efficient wafer-making equipment by analysing different approaches for improving energy efficiency (alternative combustion, optimizing isolation, waste heat recovery, etc.). In particular, two different oven prototypes were selected (due to their high-energy consumption) for carrying out extensive tests and recording measurement data:

- temperature (at 64 different positions),
- humidity (at 4 different positions),
- process data (control of heating elements, etc.)
- exhaust gases (CO, NOx, relative humidity, etc.)

Figure 31 Typical baking oven from FHW

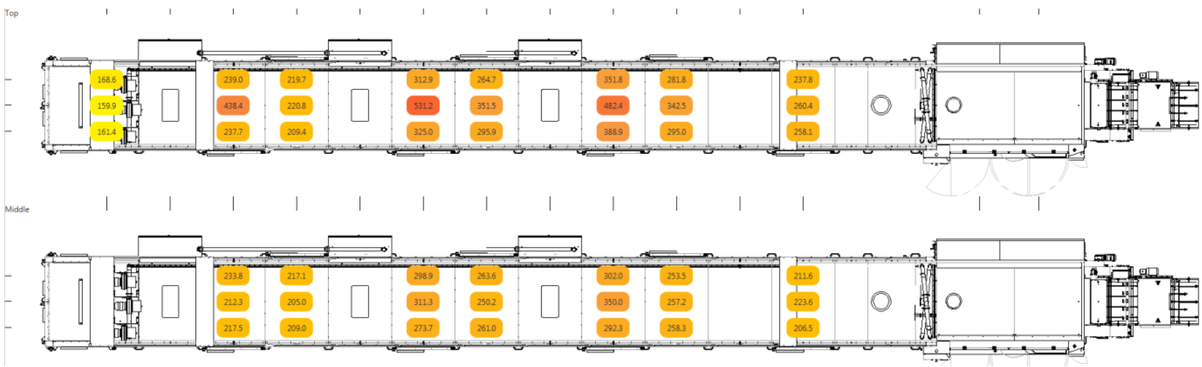


Figure 32 Temperature profile inside the baking oven during measurement

A more detailed look at heat-up and cooling phases of the ovens (Figure 31) revealed significant potential for improvements regarding production time, energy consumption and heat management. For example, a better-isolated oven is able to store internal heat for a longer period of time, thereby reducing the power (and time) necessary for subsequent heat-up. As the frequency of stand-by and setup intervals in production is expected to increase in the future (due to increasing number of production variants, etc.), these improvements promise significant savings.

Of interest for FHW were also other energy-intensive production units, mainly cooler and dryer units. Using measurements in various parameter settings (Figure 33), the intention is to investigate possibilities to increase overall efficiency by exploiting synergies between different production units, e.g. absorption chiller powered by waste heat, combining cooling and drying by means of condensation, etc. A preliminary study concerning cost-effectiveness of heat recovery for intra-process cooling purposes evaluated the cost-effectiveness of using an absorption chiller against conventional compression chiller as part of feasibility calculations including investment and maintenance costs, durability, operating costs and energy demand.

Figure 33 Measurement setup for the cooling units

Simulation:

The obtained measurement data also serve as basis for parameterizing a simulation model, which is intended to allow making first predictions on how different production scenarios (e.g. shift work in two versus one shift) influence energy efficiency, CO_2 emissions and costs.

The simulation model showcases a generalized production layout (see Figure 34) derived from seven real production lines for producing flat and hollow wafers. Using different parameter sets, the model can be tailored to different customers and products. Nearly all of the cube components could be reused from other use cases, which drastically reduced modelling and implementation effort.

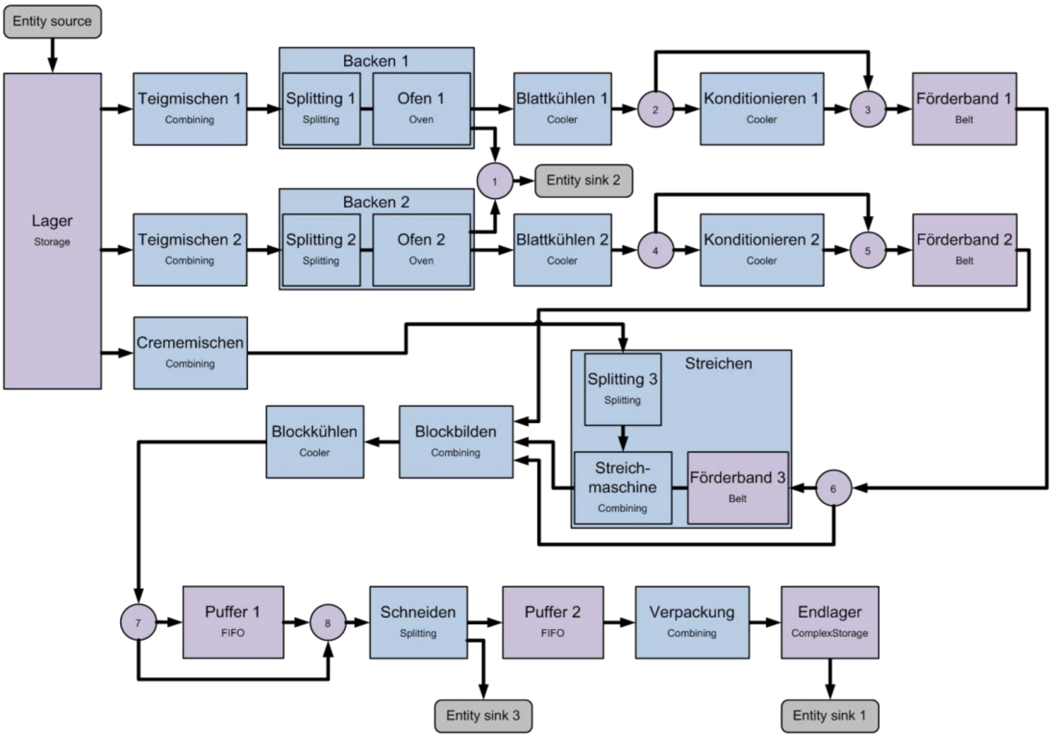


Figure 34 Production layout for the simulation

In addition, the overall simulation also features a generalized model of an energy supply system and thermal building behaviour (see Figure 35), in order to be able to investigate energy efficiency in the overall context of the entire production facility. For example, a better-isolated oven that requires less energy also produces less waste heat, thereby increasing the heating demand of the surrounding building, which might diminish initial energy savings. On the other hand, during summer, less waste heat might also decrease the building's cooling demand and enhance energy efficiency.

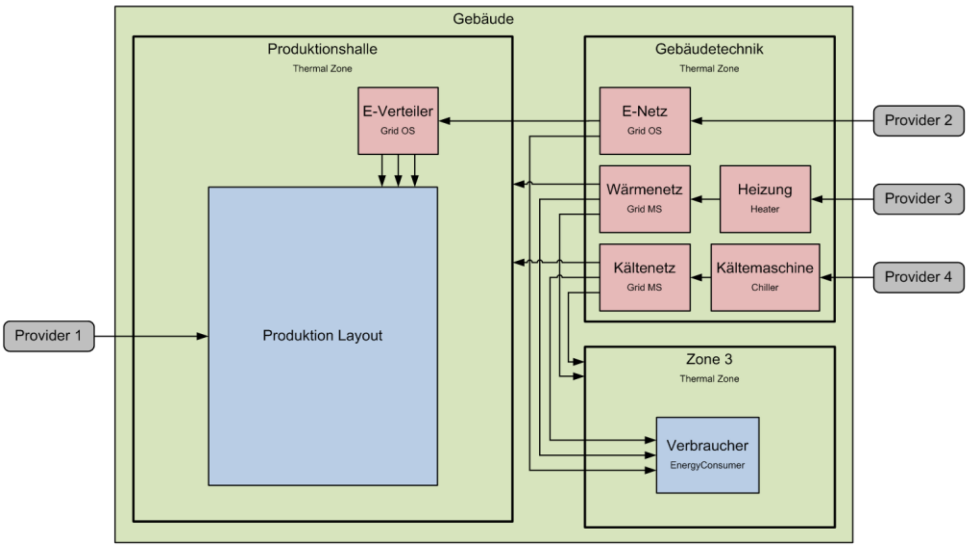


Figure 35 Building layout and energy supply system for the simulation

The implementation of the simulation model together with a database for storing simulation results as well as a user interface was carried out by AutomationX. Figure 36 shows the overall architecture. For parameter input, MS Excel was chosen (see Figure 37) because it provides a familiar interface for the users and allows to be extended easily in order to incorporate calculations of model parameters from measurement data.

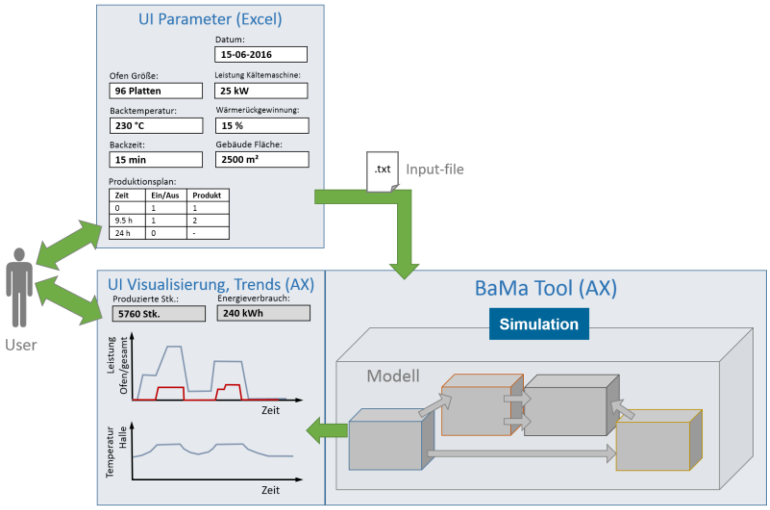
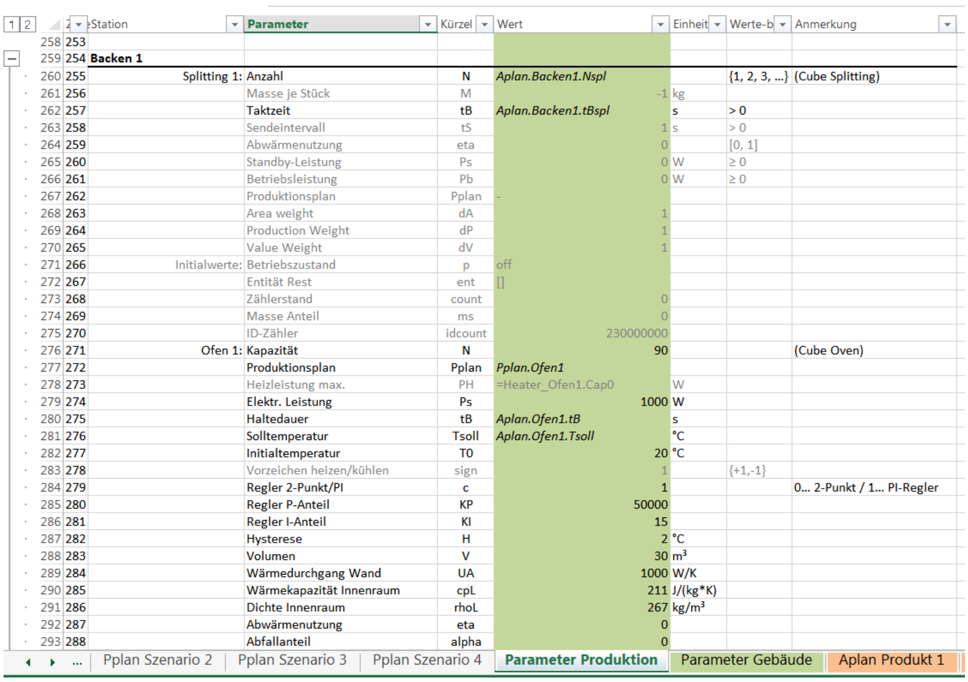


Figure 36 Basic architecture for the FHW simulation, showing a user interface for parameter input (Excel), the simulation implemented in the AutomationX software (AX) and a user interface for result visualization



	Z	Station	Parameter	Kürzel	Wert	Einheit	Werte-b	Anmerkung
258	253							
259	254	Backen 1						
260	255	Splitting 1:	Anzahl	N	Aplan.Backen1.Nspl		{1, 2, 3, ...}	(Cube Splitting)
261	256		Masse je Stück	M	-1	kg		
262	257		Taktzeit	tB	Aplan.Backen1.tBspl	s	> 0	
263	258		Sendeintervall	tS	1	s	> 0	
264	259		Abwärmenutzung	eta	0		[0, 1]	
265	260		Standby-Leistung	Ps	0	W	≥ 0	
266	261		Betriebsleistung	Pb	0	W	≥ 0	
267	262		Produktionsplan	Pplan	-			
268	263		Area weight	dA	1			
269	264		Production Weight	dP	1			
270	265		Value Weight	dV	1			
271	266	Initialwerte:	Betriebszustand	p	off			
272	267		Entität Rest	ent	[]			
273	268		Zählerstand	count	0			
274	269		Masse Anteil	ms	0			
275	270		ID-Zähler	idcount	230000000			
276	271	Ofen 1:	Kapazität	N	90			(Cube Oven)
277	272		Produktionsplan	Pplan	Pplan.Ofen1			
278	273		Heizleistung max.	PH	=Heater_Ofen1.Cap0	W		
279	274		Elektr. Leistung	Ps	1000	W		
280	275		Haltedauer	tB	Aplan.Ofen1.tB	s		
281	276		Solltemperatur	Tsoll	Aplan.Ofen1.Tsoll	°C		
282	277		Initialtemperatur	T0	20	°C		
283	278		Vorzeichen heizen/kühlen	sign	1		{+1,-1}	
284	279		Regler 2-Punkt/PI	c	1			0... 2-Punkt / 1... PI-Regler
285	280		Regler P-Anteil	KP	50000			
286	281		Regler I-Anteil	KI	15			
287	282		Hysterese	H	2	°C		
288	283		Volumen	V	30	m³		
289	284		Wärmedurchgang Wand	UA	1000	W/K		
290	285		Wärmekapazität Innenraum	cpL	211	J/(kg*K)		
291	286		Dichte Innenraum	rhoL	267	kg/m³		
292	287		Abwärmenutzung	eta	0			
293	288		Abfallanteil	alpha	0			

Figure 37 Excel User Interface for parameter input

The AutomationX software also provides a user interface for visualizing simulation results, shown in Figure 38.

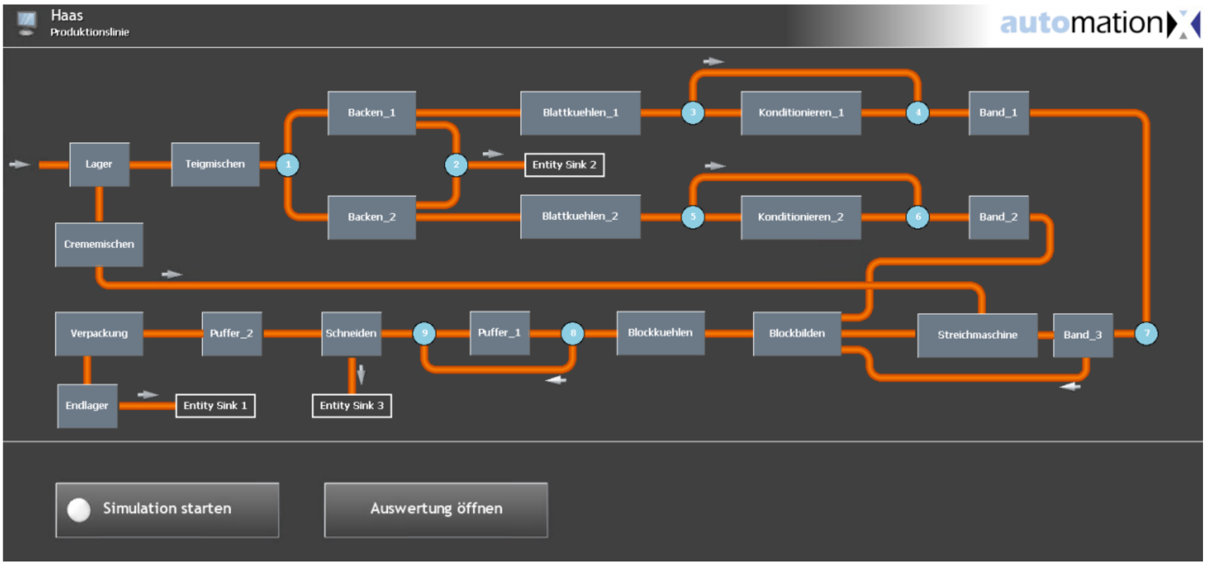


Figure 38 AutomationX user interface for results visualization

The simulation allows comparing and evaluating different scenarios and customer's use cases, e.g.:

- different oven sizes, combustion variants, heating behaviour,
- different products with varying process parameters, baking times, etc.,
- various production schedules,
- heat recovery.

These evaluations will help to gain insights into planning and operation of energy-efficient production lines.

Conclusion:

Overall, FHW has achieved significant improvements regarding planning and operation strategies of their production lines by using BaMa as an approach for holistic energy considerations. Especially energy management strategies via storage potential during stand-by times are becoming more important in the future as they provide shorter startup times, higher productivity and higher energy efficiency. FHW is now able to analyze the energy demand of the production equipment in interaction with its surroundings and optimize the overall energy consumption over time.

2.8.6 MKE

When considering the different operating states of the galvanic plant, the measurements showed a direct correlation between temperature change and energy consumption in the heating elements, the energy input through the coating process can be represented but limited to the effective coating time. The original approach of a possible energy saving by omitting the night reduction was not confirmed by the measurements. Based on the measurement data, it was possible to increase the lowering per night from four to six hours by optimizing the heating capacities in individual baths. This measure results in a saving of 13.92 kWh / night, which results in an annual cost saving of € 417, -.

The use of wet blasting systems in electroplating for the pre-treatment of the baking plates creates a high demand for compressed air, which could only be achieved with a relatively high network pressure of 7.4 bar. Since this demand occurs only for a relatively short but irregular period in the range of 4min to 15min and 4 to 10 times per shift, it is inevitable to maintain the network pressure at the level of 7.4 bar otherwise other manufacturing machines due to a pressure drop in emergency shutdown go. The aim of the measure is to reduce the network pressure depending on the blasting systems and machines used to the level required in each case and thereby reduce the relative energy input at the same amount of air. The basic requirement was therefore also the collection and adaptation of the compressed air lines. By using an optimized compressed air management system, not only the air volume to the consumption but the complete network pressure at the company premises is adapted to the consumers. Optimization is a continuous process that still has to be adapted to the most diverse consumer combinations. In this evaluation, the pressure reduction during sandblasting was taken into account at 6.9 bar and in the remaining time to 6.4 bar.

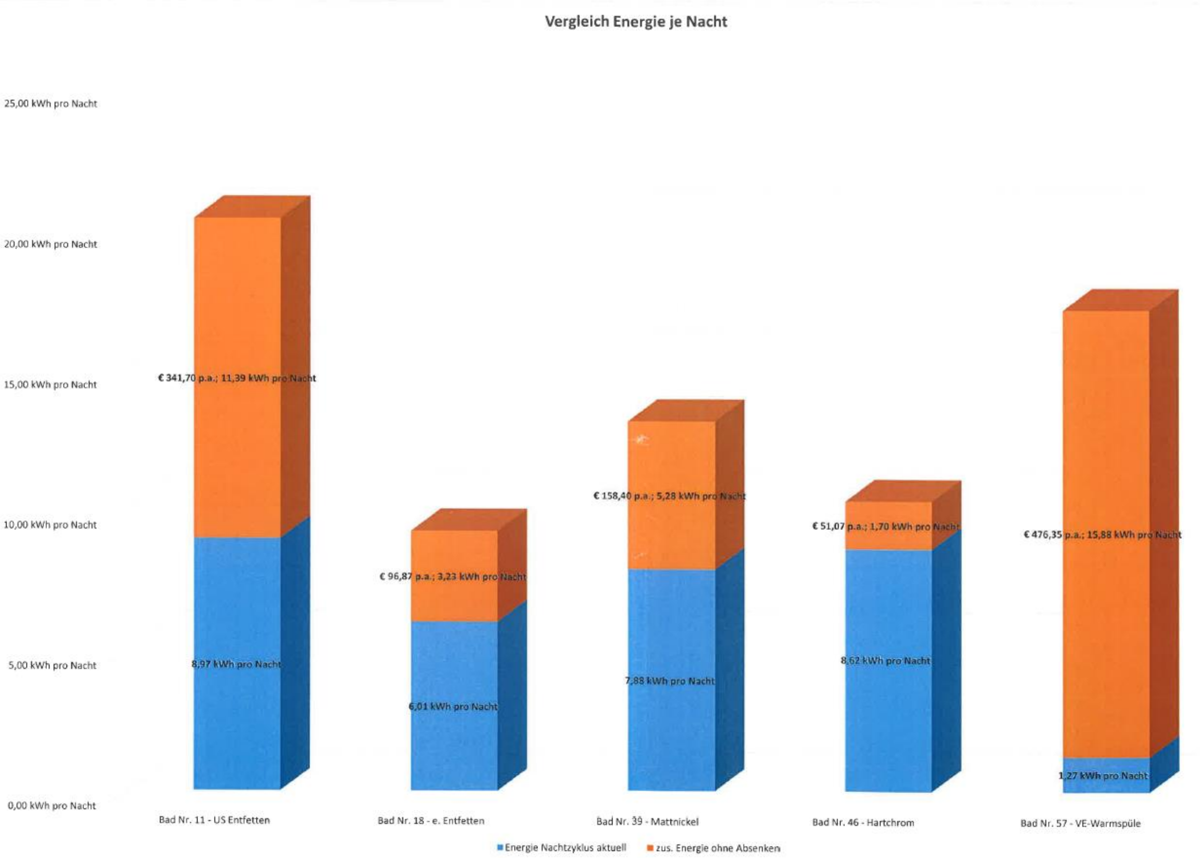


Figure 39 Energy demand per surface treatment before and after efficency measures

The sandblasting with regard to the pressure lowering and lifting we have evaluated at a consumption greater than 6 m³ / min. It is understood that the advantages of the optimization and pressure optimization of the SAM have to be borne in mind, which will have an additional impact on the reduction of the leakage quantity over a longer period. This results in a total energy saving effect of 47.588 kWh per year (extrapolated based on the measurement evaluation from 23 to 29.03.2017. This results in a saving of € 4,760 per year.

3 Evaluation results and lessons learned

BaMa tries to marry sustainability with competitiveness in industrial production, by finding a balance between energy and cost efficiency.

Industrial users that are interested in implementation of BaMa in their companies have to master many challenges. From the mapping of the production lines in a simulation model, with real production parameters for some products, to the determination of the parameters for production units in the whole production. For this task, it is necessary to have the according product master data including production data. In addition to this, usually it is required to make a field campaign to determine the energy demands of some products and production units.

After setting up a model it is helpful to organize an “objective function – workshop” with the Management and persons in authority, to detect the most important critical factors for the company, to scale them in the objective function (for example processing time, shortage, storage or energy).

The main challenge with the implementation and setting up of BaMa in a company consists in the fact that different data, consisting of master data, working plans, heuristic (rule-based) knowledge, process and setup times as well as energy related data are required and have to be understood correctly in order to build a good simulation-model. This collected data - also data gathered from measuring campaigns - must also correspond to the reality, which is not always easy for these large quantities of data. This project demonstrates the ‘time-consuming’ approach and the arising difficulties of the proposed method.

4.1 Documentation of BaMa rule base

4.1.1 Hybrid Simulation: State of the Art

This chapter gives a brief overview of existing planning methods and identifies the research gap addressed by this project. Within the scope of this project an integrated hybrid simulation was developed, enabling the modeling of continuous and discrete behavior simultaneously. It is the combination of logistics simulation, which is typically simulated using a discrete event simulation (DES), and the simulation of the energy flows, that is continuous in nature and are therefore modelled as ordinary differential equations (ODEs) or differential algebraic equations (DAEs). Since the desired planning method is aimed at practically applicable methods, the review of existing approaches is focussed accordingly. The planning approaches can be categorized into traditional approaches, meaning hands-on less sophisticated approaches that have been widely used in industry applications, simulation-based approaches and optimization-program-based approaches.

A good representative for traditional approaches is Energy Value Stream Optimization [38] – a technique to optimize production processes systematically in a static, one-time improvement effort. Although potentially affecting PPC, these methods are not able to provide a PPC/APS functionality and the planning principles are too static to be utilized in a dynamic planning method such as an APS.

Simulation-based approaches try to capture the system behaviour in the form of a simulation model, and near-optimal production plans are compiled through either manual experimentation or simulation-based optimization techniques, in which the simulation serves as an evaluation function. Two approaches stand out as representatives of two sub-groups: Thiede [39] uses a multilevel simulation to model the material flow, production equipment and components of the energy system. Although dynamically coupled, the limited interaction between the models does not allow for detailed consideration of interactions between the energy system and the material flow. The optimization is conducted manually. The second representative is the approach by Rager [40], which contains a simulation-based optimization. It utilizes a Discrete Event Simulation (DES) restricted to the material flow and with deterministic energy consumption. The optimization variables are restricted to traditional sequencing and scheduling and do not include the control of equipment in the periphery of the production process.

The optimization-program-based approaches feature more simplified models of the real life production system in order to be formulated and computable as genuine optimization programs. None of the genuine optimization-program-based approaches can fulfil the requirements concerning a realistic system behaviour.

The following table (more details in [41]) gives an overview of the reviewed approaches, including an evaluation of the degree to which the two major requirements are fulfilled. Only simulation-based approaches fulfil the model complexity requirement. The two major identified research potentials are

- A more comprehensive modelling and simulation of the interactions between material flow and energetic behaviour of the production system, thus enabling accurate and reliable planning results.
- An optimization module that can cope with the complexity of the model and provide an automatic optimized compilation of production plans and equipment control.

Requirements \ Approaches	Thiede	Junge	Martin	Leobner	Rager	Wohlgemuth	Solding	Heilala	Michaloski	Weinert	Dietmayr	Haag	Rahimfarad	Abele	Löfgren	Cannata	Continuous Simulation	Optimization-Based
Modelling of Production System	◕	◕	◕	○	◑	○	◑	◑	◔	◑	◑	◑	◔	◔	◔	◔	○	◔
Modelling of Energy System	◕	◑	◕	◕	◑	◔	○	◔	●	◑	◔	◑	◑	◑	◔	◔	◕	○
Interactions between material-flow and thermal-physical	◑	◔	◑	◑	○	○	○	◔	◔	◔	◔	◔	○	◕	○	○	◕	○
Automatic Optimization	◔	◑	◑	○	◕	○	○	○	○	○	○	◔	○	○	○	○	○	●
Readyness for industry use	◕	◕	◔	◕	◑	◔	◔	◔	○	◔	◔	◔	○	○	○	○	○	○
Overall fulfilment of requirements	◕	◑	◑	◑	◑	○	○	◔	◔	◔	◔	◔	○	◔	○	○	◔	◔

Figure 01_41: Comparative rating concerning existing approaches

4.1.2 Hybrid Simulation approach in Balanced Manufacturing

Developing models of production facilities for the purpose of energy efficiency investigations requires incorporating aspects from different engineering domains (production machinery, logistics, energy infrastructure, building) with sufficient accuracy. These aspects usually include descriptions of material flow as well as energy and information flow. While material flow is typically modelled as discrete entities, energy flow – especially its transient behaviour – is more accurately described using continuous (differential) equations. This raises the need for a hybrid approach to modelling and simulation that combines discrete as well as continuous simulation models.

Typical hybrid simulation methods employ multi-method co-simulation [42, 43] that combines different simulation environments (on the application level), e.g. one for the discrete sub-model and one for the continuous sub-model. These sub-models can then be coupled at runtime [44] using some kind of middleware. However, as a limitation, the modeller is forced to split the overall model into different simulation environments along the boundaries of discrete/continuous modelling. In the context of a component-based modelling paradigm, it quickly becomes cumbersome to maintain modular components that incorporate both discrete and continuous behaviour within uniform boundaries, which in turn reduces their reusability. In addition, the computational overhead of co-simulation limits execution speed and thereby the

feasibility for simulation-based optimization tasks with possibly thousands of necessary iterations.
In order to be able to design modular, reusable – and hybrid – model components, other directions have to be explored that allow a tighter integration of discrete and continuous models. One possible approach, which we employed in this paper, is based on hyPDEVS [45], which is an extended DEVS (Discrete Event System Specification) formalism [46] for hybrid systems. DEVS formalisms are a formal model description, accompanied by an abstract simulator execution algorithm, and allow building models from components in a hierarchical manner by distinguishing between atomic and coupled components. For more details regarding hyPDEVS we refer to [45,47].
In contrast to co-simulation, a model description based on hyPDEVS integrates discrete and continuous model aspects on the component level (instead on the application level), thereby allowing to encapsulate material flow and energetic behaviour within the same component boundaries and making it easier develop new hybrid application models by reusing pre-defined components [48].
In order to be used within the proposed planning tool the simulation has to fulfil three major requirements:

- Support for hybrid models: The combination of logistics simulation, which is typically, simulated using a discrete event simulation (DES), and the simulation of the energy flows, that is continuous in nature and are therefore modelled as ordinary differential equations (ODEs) or differential algebraic equations (DAEs). This combination is not supported by current planning tools and thus is the main innovation of the proposed software tool.
- Modular structure of models: For the use in a wide variety of settings, the models for the simulation should feature a modular structure. This enables the development of a library of basic components of production facilities (such as belts, ovens, manufacturing equipment, HVAC-systems, thermal zones) that can be used to build the model of the facility and that can be used for the simulation.
- Description in one formalism: The integration of the simulation in an existing MES/APS can be realized by either connecting to an existing, external system or implementing the simulation environment in the program itself. For this project, the second method was chosen. As mentioned before, the usage of a co-simulation approach is not feasible for the focus of this research. Thus, the models have to be described in one formalism in order to keep the effort for development and implementation of the simulation engine as low as possible.

4 Outlook and Recommendations

Within the project, the wide range of possible applications could be shown. The modular approach helped the development team to combine parts of the methodology as needed in order to accommodate the needs of every application partner. In this respect the different technological boundary conditions regarding especially available data but also the wide range of needs formulated by the application partners where challenging.

Regarding monitoring, the major challenge in the project was the problem of data access. The availability of data was much more limited than anticipated by the project team. Additionally, the heterogeneity of data sources made parameter generation and data interpretation work intensive tasks.

Nevertheless, the interpretation of available monitoring data led to sufficiently good simulation models and the simulation methodology chosen in order to combine discrete and continuous simulation approaches proved to be a feasible choice. Using this approach, models representing all relevant aspects of a production facility could be created. The resulting simulations where a solid foundation for further investigations.

Finally in the optimization part, the created simulation models where used to create optimized operation strategies which where communicated to the respective operators in the form of recommendations. Using a customizable and adaptable target function, this optimization functionality helps to transform management decisions directly into operation strategies and therefore add significantly to the operation wide improvement processes.

Regarding further steps, two main research directions can be identified.

First, the modelling process still is very challenging and time consuming. Although the developed, modular approach with configurable models available in a library already reduced this, further improvements are necessary in order to make the developed tool commercially feasible. A promising approach to this might be to use black-box models directly and seamlessly, integrating (monitoring) data. Data coming from different systems such as SCADA, MES and ERP could automatically be combined using state of the art machine learning algorithms, which would reduce the time needed to create models significantly. For companies however, it currently is hard to access the necessary data. In order to solve this, the principle of ontology- based data access should be applied to not only provide simplified access to monitoring data stored in relational databases (RDB) within organisations but also lay the foundation for a semantically enriched data platform, where similar data from different organisations can be stored, found and shared. Therefor providing access to data based approaches to SME as well as large companies.

Secondly, the current time-demand for optimization runs is rather high. Optimization algorithms- in this case metaheuristics- need a large number of simulation runs in order to produce reliable results. These runs however are computationally intensive. This fact is true, especially when the simulation models become more complex. In order to enable the necessary number of evaluations without the drawback of high computational cost due to simulation, the application of technologies such as neuronal nets and deep- learning might be used. Those could for example be used to “learn” the behaviour of a system using simulation runs creating a trained algorithm. This algorithm in turn could be used to reduce the search area for the optimization runs significantly.

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6 Appendix

6.1 BaMa Documentation

2017

BaMa Documentation

DETAILED SOFTWARE DOCUMENTATION

BAMA KONSORTIUM

6.2 Example System Specification

Technological
Information
Logging Tool

System Specification

of the Project

TU Wien

–

Technological Information Logging Tool

Dokumentname	SystemSpecification_TILT_v1.docx
Version	1.0
Datum	2016-12-07
Status	First Version

Lastenheft Projekt TU Wien - T.I.L.T 1 17.11.2016
Version 0.2

6.3 Prototype Description MOBA

Projekt

Balanced Manufacturing

MOBA-Beschreibung

Last updated: 13.03.2018

6.4 Prototype Description SEPPI

Projekt

Balanced Manufacturing

Prototyp Beschreibung

SEPPI

Version 1.0

Last updated: 13.03.2018

6.5 Prototype Description HAAS

Projekt

Balanced Manufacturing

Beschreibung

Simulation Use Case Haas

Version 2.2

Last updated: 13.03.2018

6.6 BAMA Buildings Planners Handbook

Planungshandbuch ENERGIEKONZEPT

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6.7 BAMA Building Energy Concept

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