Energy efficient operation of industrial facilities: the role of the building in simulation-based optimization

G Gourlis and I Kovacic
Integrated Planning and Industrial Building, Faculty of Civil Engineering, TU Wien, Austria
Email: georgios.gourlis@tuwien.ac.at

Abstract. Energy efficiency of industrial facilities is a set goal towards developing a sustainable future. Many production facilities though are still not operated at a highly efficient rate in terms of energy use. The complexity of industrial environments requires an integrated analysis of all subsystems – production processes, logistics, building and technical building services – to grasp full optimization potentials. The use of simulation tools provides significant benefit in energy demand modeling and prediction, making its application essential for planning and management of energy efficient industrial facilities. Building Energy Modeling (BEM) and Manufacturing Process Simulation (MPS) have been used by researchers for analyzing mostly building related and process related conditions respectively. A novel approach is the holistic assessment by combining capabilities of BEM and MPS into one simulation environment. Such a hybrid simulation application has been developed within the research project Balanced Manufacturing (BaMa), addressing all subsystems of a production plant. However, the actual condition of a facility, the type and requirements of the manufacturing process, the level of implemented automation as well as the available infrastructure are decisive for the application of the appropriate simulation-based optimization method. Focusing on the subsystem of the building, this paper examines its function within two different approaches for energy demand optimization, through the use cases of industrial facilities with different characteristics. The first case focuses on the building and its components, utilizing BEM, the second on the production processes, utilizing the BaMa method. Thereby the use of Building Information Modeling (BIM) as knowledge database for the simulations models is discussed and the integration of all industrial subsystems is analyzed. The role of the building in each case is highlighted, addressing its benefits and drawbacks.

1. Introduction
The industrial sector holds an important position in developing a sustainable future. Energy efficiency is certainly a major aspect towards this direction with a positive economic and environmental impact. Globally the industrial energy consumption accounted for 54% in 2014, deviating depending on the region, with the US and the EU accounting for 34% and 25% respectively, whereas China for 72% [1]. Although energy efficient operation has not been an initial objective for many production facilities, the increasing energy and raw material prices, the necessity of complying with stricter regulations as well as the rising public awareness on resource consumption and climate change, which pose a challenge on corporate images, leads the manufacturing industry to monitor, manage and try to reduce its energy demand.
State-of-the-art towards achieving industrial energy efficiency is the utilization of simulation tools for predicting energy demand and identifying optimization potentials [2]. Building Energy Modeling (BEM) and Manufacturing Process Simulation (MPS) are mature simulation analysis techniques which find application in the industrial sector. BEM is usually used to analyze thermal building envelopes in the residential and commercial sector and its application on industrial facilities has begun in the recent years [3, 4]. MPS is traditionally used for optimizing manufacturing process lines, analyzing machinery utilization and throughput. Regarding energy assessment, commercially available BEM software usually limit their scope on a certain area, that of the building and HVAC systems [5]. MPS on the other hand do not focus on the energy use between manufacturing equipment, utilities or the building [6]. The complexity of industrial environments requires, however, an integrated analysis of all interconnected subsystems –production process, logistics, technical building services (TBS) and the building– by combining capabilities of BEM and MPS to grasp full optimization potentials [7].

Such an approach for a holistic assessment was developed within the research project Balanced Manufacturing (BaMa) [8]. Utilizing a single hybrid simulation environment, BaMa implemented continuous aspects of energy flows, addressed in BEM, and discrete aspects of material flows, addressed in MPS. The project resulted in a simulation-based toolchain that integrates energy demand as well as carbon emissions as control parameters in industrial facilities and introduces energy efficiency as a steering value into a factory’s operational planning.

This paper examines the role of the building in simulation-based approaches for energy efficiency optimization in manufacturing plants. Based on the use cases of two operating factories, the study compares the BEM and the hybrid BaMa approaches aiming to identify benefits and drawbacks of each. Thereby the use of Building Information Modeling (BIM) as a knowledge database for the simulation model is discussed. The suitability of each method is analyzed, regarding available infrastructure, level of digitalization and anticipated optimization targets of an industrial facility.

2. Industrial simulation-based energy assessment

Simulation approaches used in the industrial sector can be categorized in those focusing on the energy modeling of the building envelope utilizing BEM, those focusing on the energy modeling of the manufacturing process chain utilizing MPS and last the holistic methods taken into account both the building and the processes [9]. This study investigates the building related aspects, therefore solely MPS methods will not be further analyzed.

As already mentioned, industrial plants are consisted of four interconnected subsystems, a schematic representation of which is shown in Figure 1. Parameters concerning the subsystem of the building, that have an impact on the energy demand, are mainly located in the building envelope and daylight conditions, e.g. solar gains. TBS is the actual consumer of the energy demand for heating, cooling and ventilation of the spaces (HVAC) as well as for the media flows, such as compressed air, cooling water or steam. Due to their nature, building and TBS subsystems are modeled with continuous flows in energy simulations. On the production level, machine and production chain models have energy as well as material flows of products. These processes constitute the manufacturing energy demand and are mainly addressed via Discrete Event Simulation (DES). Lastly, logistics during the production process with transport and handling actions or afterwards as storage contribute to the total energy demand of the facility, also incorporating material flows, therefore modeled with DES methods.

2.1. BEM-based industrial modeling

BEM simulation by default implements a time-driven modeling approach, where time is a variable that is incremented at predefined intervals and all computation is conducted for each time-step. Usually the main objective of BEM models is to find optimum solutions regarding the building geometry and thermal envelope as well as HVAC systems configurations. Available BEM software couple thermal building models and HVAC models, commonly utilizing a simpler thermal view of the building’s spaces than that of CAD models. However, the employment of BEM simulation in industrial facilities for assessing their energy demand is more challenging than in buildings of the residential and tertiary sector,
as internal heat gains from manufacturing activities can have a significant impact on the desired indoor conditions and their scheduling can vary greatly overtime, given production demand and economic cycles [10]. Therefore, manufacturing internal gains are usually introduced in these models as simplistic operating schedules, as current tools cannot accurately incorporate the discrete character of industrial processes [11]. These heat gains can be either assumed based on installed equipment loads or directly measured in case of an operating production chain, with the first though potentially leading to disputable results and the second being restrictive to existing production configurations. The examination of alternative more efficient machinery configurations is thus a laborious procedure. Furthermore, logistics related energy demand is possible to be assessed, except auxiliary energy from HVAC components, regarding special temperature conditions for sensitive products in storage rooms.

Figure 1. Energy flows and interaction of subsystems within a factory.

2.2. BaMa modeling approach
BaMa implements a generic modular approach to model all factory subsystems in a single platform, aiming to the flexibility and reusability of the models. The core modular element of BaMa is the cube. Cubes represent physical parts of the facility and are mapped into mathematically formulated virtual counterparts in a simulation model. They are defined and connected through common interfaces, combining three kinds of flows: energy, material (incorporating the immediate value stream of products) and information (control and demand related). Energy flows and related carbon emissions are treated as continuous values, whereas material and product flows as discrete entities. This resulted in creating a hybrid simulation environment based on the Discrete Event and Differential Equation System Specification (DEV&DESS) [12] as a hybrid Discrete Event System Specification DEVS formalism [13], based on Parallel DEVS (P-DEVS) [14].

The holistic BaMa approach links the four subsystems of building, TBS, production processes and logistics, by incorporating them in a hybrid simulation-based toolchain for monitoring, predicting and optimizing industrial energy demand. Components of all subsystems are modelled as cubes. The building subsystem consists of the building and the thermal zone cubes. The first represents the solid constructions, i.e. walls and slabs, and calculates the heat exchange between neighboring thermal zones and to the outside. The second describes the thermal condition of a space, calculating the heating and
cooling demand. Comprehensive information on the cube models can be found in [15], as a detailed presentation would go beyond the scope of this paper.

The aim of the BaMa toolchain regarding the role of the building is to deliver information about auxiliary energy demand, such as space heating and cooling, based on weather conditions and production schedules. Together with production and logistics needs, the toolchain can predict the energy demand of the entire facility. This enables optimization of the systems' operation via algorithms, by using parameters as energy saving, costs reduction or time as target functions. An extensive description of the BaMa methodology is available in [16, 17].

2.3. BIM as input database

BIM, defined as "a digital representation of physical and functional characteristics of a facility" [18], offers potentials through the creation of a joint knowledge database, for follow up analysis of buildings and building systems in terms of energy performance. Still, data rich BIM models need to be simplified to provide only that information, essential for the accomplishment of a simulation analysis. Extensive research has been conducted on data transfer from BIM to BEM tools, but the process of BIM-based BEM is still in development, not yet being able to generate reliable models ready for analysis from initial architectural BIM models, with information loss being a common problem [19]. In the field of industrial facilities, BIM becomes a favored tool for designing, planning and managing this complex building typology, providing benefits in terms of collisions from the integrated discipline models (e.g. architectural, structural, MEP, machine floor layout and infrastructure). However, research on industrial BIM-based BEM assessment shows interoperability issues and portrays the procedure as too work intense [20]. BIM models hold yet potential to be used as input information for holistic industrial simulation tools, as that of BaMa [21].

3. Use case application

The two simulation approaches, BEM and BaMa, have been applied in two operating industrial facilities in Austria. Use case A lays focus on improving the building itself, while objective of use case B lies in the energy optimization of the production process. Consequently, the BEM approach was applied in use case A and BaMa in use case B. Further characteristics of each facility, decisive for the application of each methodology as presented below.

The BIM models of both use cases in Autodesk Revit are shown in Figure 2. The model of use case A was constructed from available documentation and on-site audit to serve as an input model for BEM, whereas in use case B the original architectural BIM model of the building was used [20]. In both cases, BIM models were simplified in respect to the actual geometry and space partitioning to facilitate data transfer to BEM and BaMa respectively. Use case A was modelled from scratch according to these principles. In use case B, the original model was modified by redefining room-stamps and internal boundaries, representing the necessary thermal zones, corresponding to the modular cube approach of BaMa.

![Figure 2. BIM Models of use cases A (left) and B (right).](image-url)
3.1. Use case A – BEM

Use case A studies a single story metal processing facility, categorized as light manufacturing with a gross floor area of about 20,000 m². Typical for existing industrial building, this facility is a result of multiple expansions to a 1920s historical hall until the 1990s, with different building envelope constructions according to each phase. The older part of the factory has thick brick masonry walls and an uninsulated wood sheathing roof, whereas newer spaces, insulated metal cassette walls and sandwich roof panels. Figure 3 shows the thermal model of the building simulated with EnergyPlus [22]. The building is naturally ventilated, uses ceiling radiative panels and local fan coils for heating and there is no mechanical cooling. There are no building management systems (BMS), no energy monitoring systems and no automated production planning system. The manufacturing process chain is highly variable based on production orders demand with no standard-defined sequence and is planned manually according to daily necessities. On the other hand, machinery used is highly automated. Therefore, use case A is characterized by an overall very low level of digitalization.

The objective of use case A was to assess the energy optimization potential linked with the refurbishment of the older part of the building. Especially the impact of retrofitting the roof, which measures 82% of the building envelope area. Thus, a BEM approach was selected, with manufacturing heat gains calculated based on machinery energy consumption measurements during a period of a typical production month. Machinery operational hourly schedules were defined according to mean values of the monitored machinery on daily basis. Energy consumption of electrical lighting was also monitored and provided as an input to the BEM model. Regarding the building envelope, its geometry was exported in BEM from the created BIM model, however, semantic data regarding constructions were added manually.

Results showed, that the replacement of the older part of the roof with a new insulated roof skin as well as the replacement and area reduction of existing saddle single glazed skylights with raised monitor roof double glazing skylights, largely contributed in 52% reduction of the building’s annual heating demand. Thus BEM provided an optimized configuration for the building envelope retrofit. A detailed presentation of this use case can be found in [23].

Figure 3. Thermal model of use case A, on the left side the older and on the right side the newer building part.

3.2. Use case B – BaMa

Use case B examines an industrial bakery, considered as moderately energy intensive and featuring a complex material flow. The factory is housed in a recently constructed new building, with production areas arranged mainly in double-height spaces on the ground floor and peripheral and administration areas in the mezzanine and upper level. The gross floor area measures circa 12,000 m². The building is heated and cooled via a mechanical ventilation system, having strict conditioning requirements for production spaces with an air temperature range between 24°C and 26°C. The cold storage and freezer specifications require a maximum temperature of 4°C and -22°C respectively. In packaging and commissioning spaces as well as in the raw material storage the temperature is allowed to range between 18°C and 26°C. These requirements are controlled by the buildings management system (BMS), which is embedded in factory’s operational planning system together with the enterprise-resource-planning...
system (ERP). Production consists of nine major highly automated machines, linked by nine conveyor belts with junctions as well as three storage units. The products, baked or deep-frozen, use different material flow paths – mainly with and without passing through an industrial oven – and require different process parameters, e.g. temperatures and processing times on machines. Use case B is depicts a high level of industrial digitalization.

As this use case deals with a new factory, all subsystems are considered to be planned in a relative optimum way. This means that the building envelope, the efficiency of the TBS and the machinery itself are the “best in class” regarding their performance. Therefore, the energy optimization potential in here lies in the efficient operation of the production process, taking into account synergies of all interconnected subsystems. Therefore, the BaMa approach is applied, dividing the facility in cubes, as of section 2.2. The structure of the hybrid simulation model, including both energy and material flows is shown in Figure 4. The building is simplified in four thermal zones cubes, corresponding all production areas, the packaging and commissioning area, administration spaces and the technical rooms. Boundary conditions and adjacencies of these four zones are defined by the building cube. Data for the parametrization of the building and thermal zone cubes are collected manually from the simplified BIM model of the facility.

The whole BaMa toolchain is implemented by first monitoring actual operational information from the BMS and ERP systems, using them afterwards to parametrize the hybrid simulation model and lastly employing a genetic algorithm (GA) which considers the targets of energy, time and costs efficiency as well as restrictions resulting from given degrees of freedom, resource availability and product quality. The GA aims especially in minimizing energy demand with the utilization of synergies, peak load management and efficient use of available equipment. Further details can be found in [24]. Results indicated a reduction of the overall energy consumption up to 30% [25].

![Figure 4. Structure of hybrid simulation model in BaMa for use case B.](image)

4. Discussion
The two use cases presented in section 3 designate the wide spectrum of goals regarding industrial energy efficiency. There are various factors influencing the final energy demand of a facility, which is becoming an additional management objective alongside product quality, costs and time efficiency.
Available infrastructure and the level of digitalization are decisive for setting the optimization targets and consequently the suitable tools to achieve them.

The holistic simulation-based assessment of all subsystems constituting a factory, as that of BaMa, is suggested as the most comprehensive approach [9]. However, use case A points out that older factories, with a low digitalization level are probably not capable of deploying holistic methodologies. There the subsystems of the building and the TBS, from an energy assessment point of view, can be regarded as equal to the manufacturing processes in terms of their energy saving potential. Therefore, the BEM-based building envelope optimization of use case A is an essential step towards an improvement of the overall energy efficiency.

This brings us to the point of assessing the role of building modeling in the two presented simulation-based approaches for energy efficiency optimization in manufacturing plants. The two approaches have a fundamental difference in the way the treat the building, with BEM having it in its core, while BaMa considering it as the boundary enclosing its core, namely the production process. The building in BaMa is thus an auxiliary component of the industrial facility.

This difference can be seen in the capabilities comparison of both simulation approaches in Table 1. BEM provides detailed modeling options for building characteristics as well as HVAC systems, whereas the only further industrial subsystem that is included is machinery, in a simplistic manner. On the other hand, the BaMa hybrid simulation includes all industrial subsystems, with that of the building though being intensely simplified. The simplified building model, lacks a detailed representation of the geometry and addresses daylight and solar gains only by a total g-factor of the transparent elements, based on a set diminution factor of any existing shading (Fc value), not considering shading geometry of the building constructions. Furthermore, thermally activated building systems (TABS) and natural ventilation strategies cannot be modelled in the BaMa hybrid simulation. It should be noted though that the building models in BaMa are not utilized like traditional BEM for a building thermal and energy performance assessment but serve the role of interacting with other subsystems and the external environment, as the hybrid simulation is not aiming to optimize the design or technology of the industrial building itself or of the available TBS. To this extent it allows a qualitative and quantitative analysis of the whole industrial facility in terms of energy efficiency.

| Building | TBS | Production | Logistics |
|----------|-----|------------|-----------|
| Envelope | HVAC | Machinery | Prod. chain | Storage | Transport |
| BEM      | ✔   | ✔         | ✔         | ✔       | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| detailed | detailed | no input | no input | no input | no input |
| BaMa     | ✔   | ✔         | ✔         | ✔       | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   | ✔   |
| simple geometry | - daylight control | - detailed | - no TABS | - no natural ventilation |
|          | - simple shading factors | - detailed |
|          | - no geometry shades | - detailed |

Table 1. Capabilities comparison of both simulation approaches.
Taking aforementioned into account, it can be argued that BEM-based energy optimization is suitable at a first stage for assessing the building and TBS optimization potential, especially for older industrial buildings. Yet when advancing on an integrated analysis of the whole factory, suitable for new or refurbished buildings, the hybrid nature of the BaMa approach, combining energy and materials flows, incorporates the multifaceted features of manufacturing plants and can better predict energy saving potentials according to actual restrictions.

Under this perspective, already developed BIM models of new facilities, like that in use case B, or older ones after an extensive building refurbishment, like use case A, could be used to provide necessary parametrization data for the simplified building models in holistic tools such as the BaMa toolchain. In use case B this has been done manually, however, a potential automated acquisition of building and TBS related information from BIM models could assist the implementation of such simulation-based methodologies in operating industrial facilities.

5. Conclusion
Simulation-based optimization can provide insight on the energy saving potential of manufacturing facilities. This paper studied two simulation approaches for energy modeling of industrial environments, with one focusing on the building aspect utilizing BEM and another focusing on the production processes, incorporating the building and TBS as auxiliary systems in a hybrid simulation within the developed BaMa toolchain. Use case applications showed that the level of digitalization of the factory and available infrastructure are decisive factors for selecting the appropriate method. In older facilities which have a building refurbishment potential, the modeling of the building holds an important role towards energy efficiency. With this regarded as the first step, the next one is a holistic assessment of all factory subsystems, where a simplified building modeling serves the role of providing the boundary between the production processes and the external environment, influenced by internal and external conditions and having an impact on the final overall energy demand.

In the case of the BaMa toolchain, further research is necessary for acquiring data available in existing BIM models to facilitate the parametrization of the building related subsystems in the hybrid simulation model environment. This would promote BaMa implementation in operating manufacturing plants in order to provide valid optimization alternatives of the production planning, based on actual capacities and limitations.

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