Integrated Factory Modelling – Enabling Dynamic Changes for the Factory of the Future at the Example of E.GO Mobile AG

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Abstract. Fast-moving changes in products, materials and process technologies require factory planning processes and procedures to be flexible and dynamic. Today, most factory planning projects are missing their budget (72%) and time targets (60%). To reduce these deviations, digitalization is key to success, but in current approaches, coordination between different planning disciplines is missing as well as different technology maturity levels prohibit automated interfaces. The Integrated Factory Modelling (IFM2) is an interdisciplinary planning approach for Green- and Brownfield factories coordinating all planning disciplines from infrastructure to process planning across the factory lifecycle. Therefore, the Integrated Factory Model (IFM) as a single dataset is established for all planning participants, accessible everywhere and on every device. Collaboration is enhanced by the working mode with an agile factory scrum process. Based on the IFM user-specific smart expert tools have been developed supporting planners and managers.

As a result, planning processes could be improved significantly, reducing costs by 20–30%, saving one-year planning time for a Greenfield and reduce planning failures significantly. IFM was initially applied and introduced to the e.GO Mobile AG, which is used as an example showing real-life use cases, challenges as well as next development steps.

Keywords: Factory of the future · Factory planning · Coordination · Single data source · Agile planning

1 Introduction

Manufacturing companies need to be adaptive and dynamic to solve future production challenges. Shortened product life cycles, e.g. as a result of new digital functions or new production technologies caused by new materials and technologies, lead to

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frequent changes in factory requirements and require a continuous factory planning [1]. Additionally, the use of a wide range of IT tools in factory planning has become essential to manage complexity but also, factory planning is expensive and often time-consuming. Time and financial budget targets are usually not met as a result of various challenges in the planning process [2]. Frequent changes in requirements during the planning process lead to time loss and repeated planning efforts. In addition, the strong parallelization of product development and factory planning often forces planners to make assumptions, even about basic product characteristics such as material and production time. It is also associated with various challenges such as shortened planning phases, increased frequency and complexity of factory planning tasks. The main challenges facing factory planning today are [3]:

(1) Need for dealing with various planning tasks simultaneously involving multiple stakeholders
(2) Limited availability of information and resources
(3) High expectations in limited time and at an effective cost
(4) Need to keep up with continuous reorganization of production flows and layouts

In addition, Schenk [4] counts the requirements for future factory planning and the factory operation to be the follows:

(1) high planning speed and reliability;
(2) reliable knowledge already at the planning stage for the operation of a factory before product start-up;
(3) change of understanding from the unique, project-related to the permanent planning of individual phases of the factory life cycle (holistic project management) and the permanent management task thus required;
(4) integration of new participative planning and control methods and tools in connection with the unity of planning and control of dynamic processes and factory systems;
(5) holistic consideration of the planning objects across different object structure levels;
(6) extension of the consideration levels (from the market, company, process perspective);
(7) change of the planning objects by cross-linking of enterprise, factory and competence networks.

Looking especially towards Brownfield planning, the integration of new and innovative materials is challenging planners significantly. For example in automotive production, new production processes change the value streams significantly and lead to new and additional equipment which needs to be fit into the existing factory.

To summarize these requirements, new factory planning approaches need to be collaborative and cross-discipline beside of knowledge-based, dynamic and fast. This leads to the assumption that the today's planning challenges are party result of too many interfaces as well as to less cross-discipline understanding. To solve this and fulfill the named requirements named above, a new factory planning approach is required to ensure a collaborative planning process.

2 State of the Art

2.1 Factory Planning

In a cross-sector definition the Association of German Engineers (Ger. Verband Deutscher Ingenieure (VDI)) defines factory planning as a

> "Systematic, objective-oriented process for planning a factory, structured into a sequence of phases, each of which is dependent on the preceding phase, and makes use of particular methods and tools, and extending from the setting of objectives to the start of production [5]."

Spur and Schmigalla give another definition. They differentiate themselves from most other definitions due to their broad understanding by considering and focusing on the convertible and flexible factory. Thus, considering the frequent changes in their environment and consequently their repeated adjustments. According to their definition [6], factory planning

> "is the predestining design of factories. The factory is to be planned according to economic goals as well as according to the requirements of the working people and the environment."

According to them, factory planning contains of the analysis, goal setting, function determination, dimensioning, structuring, integration, and design of factories as systems as well as their subsystems, elements, substructures, and processes. [6] To better understand factory planning on greater detail, the key subject and objects in the planning process, the factory and the factory planner, shall be explained as well.

2.2 The Subject: Factory

Bergholz classifies the objects of factory planning as a cube with three dimensions. All objects of a production system are allocated within categories (organization, processes and resources), hierarchic levels and functions (processing, transport, storage and supporting functions). Due to external and internal impulses, the factory as an object is continuously under pressure, which results into the following examples of driver of change [7]:

- global linked production of goods;
- individualization of the products;
- integrated products and services;
- local changes in environment and society.

Those drivers make it essential to continuously adapt and re-plan the factory and therefore necessitate the process of factory planning.

The staff responsible for operating the factory planning project is key for the success of the project. The project team can be divided into the internal project team, which are responsible for the operational planning and coordination during the project, and external partners and influencers to the team [8]. As an example, participants in a project can be listed as following:

An internal project team consisting of (extract)

A. Project coordinator
B. Production and process planner
C. Production IT planner
D. Layout planner
E. Quality planner
F. Logistics planner

(1) Additional external influences on the project are provided by (extract)

G. Stakeholder/Management
H. Engineering department
I. Factory Operator
J. Architect, External Building teams and General contractor
K. Equipment supplier

Considering the preceding description of the complexity of the stakeholders, it becomes clear that coordinating them with the use of a classical project/team structure can lead to significant communication and information coordination problems. In worst case part of the project team loses time and ability for actual planning due to the high coordination effort. A study by Bracht stated that the average planner just uses 20% of his working time for conduction planning activities. For this reason, a new type of project structure must be sought, as shown in Fig. 1, to efficiently including a growing number of experts [9].

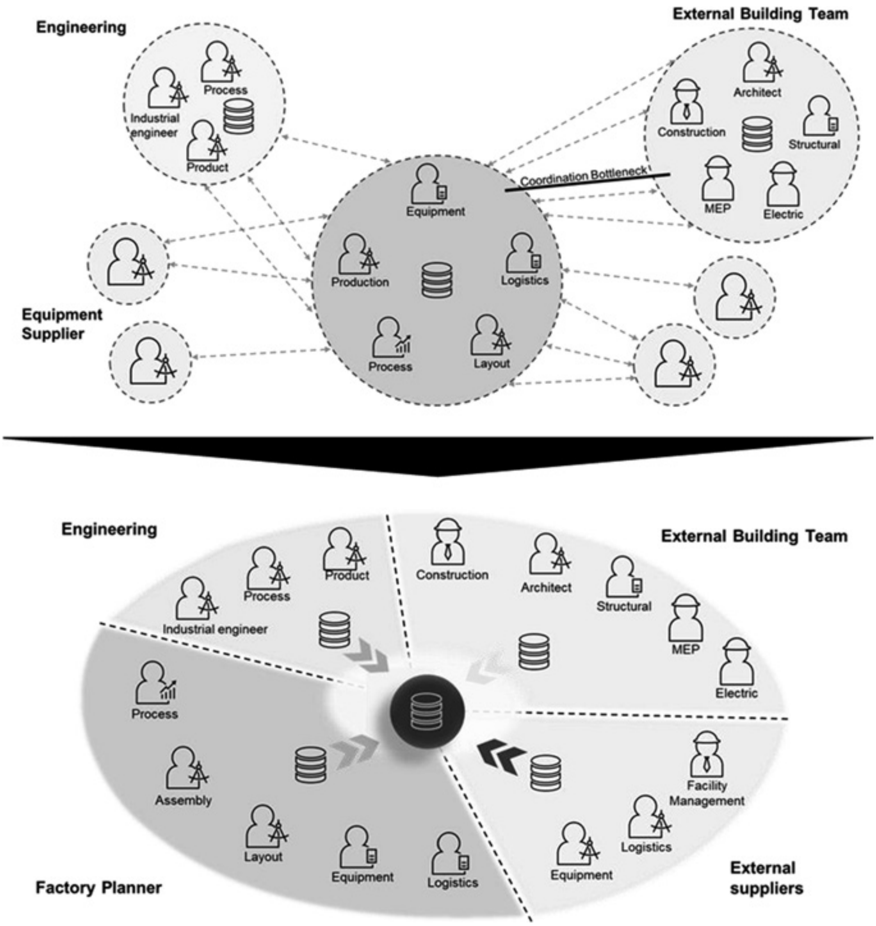

Fig. 1. Factory planning project teams: from traditional centrally organized planning teams structures to data based collaborative planning teams

2.3 Digital Factory Planning

Digital factory planning is the concept of carrying out planning processes with the assistance of various IT tools. It can be applied to both, greenfield and brownfield, factory planning projects. The procedure for the digital planning of a factory starts with the creation of 2-dimensional basic layouts and ends with 3-dimensional CAD models of the entire factory. Digital tools will lead to major changes in the way organizations function and in the content of work for many employees in industrial companies [10]. Various IT tools support factory planning and can be summarized as digital factory planning tools. Digital factory planning is characterized by three elements [9]:

(1) Data management is digitally integrated into a single model: The required data from products, product programs, processes, and resources, etc. must be gathered, created, adjusted and provided at different places during the planning process. Therefore, the task of data management is to provide and maintain an up-to-date and continuous data structure during the entire planning process
(2) Exemplary representation: With the increasing performance of computer systems, complex graphical representations as user interfaces in digital factory planning have become state-of the art. With this development, it is possible to carry out and visualize planning steps in a realistic computing environment. This enables factory planner to check and improve the dimensioning of product plants and process designs during the planning phase in a digital environment.
(3) Simulation as a forecasting instrument: By using three-dimensional simulation applications, the behaviour of complex systems such as a factory can be reproduced. The planning result can thus be tested and optimized before its realization. In particular, spatial processes such as collision tests for robot programming or the design of assembly processes can be performed. Furthermore, process flows, product dimension fittings or value streams can be mapped and simulated or tested.

The choice of IT specialist tools for digital factory planning has increased significantly. The tools must be coordinated in such a way that their functionalities build on each other or complement each other without causing interface problems. In this way, the entire digital planning process can be implemented within a single software architecture and inefficiencies can be avoided. The development of such a software architecture, which also displays the entire factory with all participants, is still the essential basis of digital factory planning. Furthermore, the software architecture should consider the three elements of digital factory planning discussed above [9].

In recent years, the construction industry faced similar challenges to those faced by factory planning and developed a. To address these challenges, the concept of building information modelling (BIM) was developed. The model is defined by international standard ISO 29481-1:2010 (E) as a "digital representation of physical and functional characteristics of any built object that forms a reliable basis for decisions" [11]. BIM is realized with object-oriented software and consists of parametric objects representing building components [12]. A completed building information model contains precise geometric and informational data, which is required to support the design, manufacturing and construction activities, needed to realize a building [13]. BIM can be viewed as a virtual process that incorporates multiple attributes of a facility within a single virtual model which can be used by the stakeholders from various disciplines to collaborate [14].

For this reason, the BIM approach can be used as basis for a digital and networked planning process, which is supplemented by the requirements of digital factory planning.

3 Integrated Factory Modelling

The methodology of Integrated Factory Modelling (IFM) is designed to meet these challenges. Therefore, ideas of the BIM methodology have been enhanced by production needs with the target of enhancing the planning collaboration of the project team.

The IFM works with the idea of five main project phases: During the first phase, the so-called planning phase, process concepts, an initial rough 2D layout and the basic material flows are developed. During the design phase, a 2D & 3D CAD model of the factory is created, which serves as a data basis for the further planning process. The next step is to use technologies like virtual reality for design reviews of the CAD-Modell and carrying out a clash detection and issue Management as part of the validation phase. The fourth phase, the build phase, is where the planning is transformed to stone and concrete and the model is used for a rigorous site management and progress monitoring. Therefore, regular plan/is comparisons are conducted. During the operating phase a predictive maintenance approach is used. In addition, the generated data from the operate phase is made available as a data basis for the future re-planning as well as continuous time (4D-planning) and scenario planning (5D-planning). This basically enables a continuous improvement process and reduces the information collection time and effort along the factory lifecycle.

To ensure that all stakeholder are properly aligned during the process, the IFM is using a factory scrum process. Each planning sprint has a duration of about two to four weeks, which the planning participants use for enhancing their planning maturity. During each sprint meeting at the end of a planning period the coordinated factory model is reviewed, changes are discussed and documented in the model as well as new tasks for the sprint are defined. Additionally, daily spring meetings can be arranged in the planning groups to align in small teams.

Therefore, the three main characteristics of the IFM methodology, which are displayed in Fig. 2, are now explained in detail:

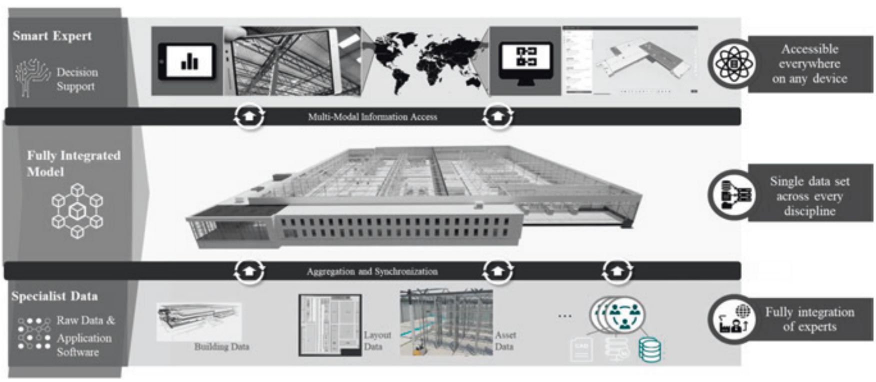

Fig. 2. Interrelations of the IFM model

(1) One single dataset across every discipline

All planning activities are operated and documented in a centralized planning model. The factory model always reflects the current planning status of all planners, making changes and errors immediately visible by automated collision control. Errors are thus detected and eliminated early in the planning process. Since this is done purely digitally and virtually, error costs are dramatically reduced. To achieve all this, IFM must be integrated in all planning phases of the factory planning process, from the design of 2D layouts to the virtual reality representation of the model in a 3D environment, as well as all disciplines. All planning activities carried out by internal and external parties must be aligned and synchronized with the platform. This also includes the product development team which connects its current product model with the IFM model. Due to this layout relevant changes can be recognized and implemented at once. For direct integration of supplier, IFM provides flexible extensions of the platform. The suppliers will get their own enclosed space on the platform and will be connected to the processes of IFM without sharing of all planning information (see Fig. 3). In the case of IFM, the 3D model of the factory represents the central interface to the planning process, which can be used throughout all life cycle phases of the factory

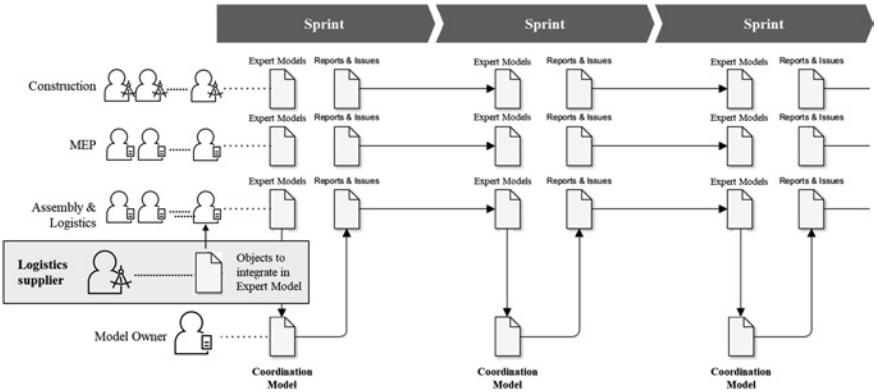

Fig. 3. Integration of specialist planners and expert processes of IFM

(2) Fully integration of experts

The CAD factory model consists of many individual part models, which in turn are divided into further part models down to the level of individual objects, as can be seen in Fig. 3. Typically, the production is split into assembly, logistics, quality and more areas of the factory are modelled as a separate sub-model. The validation of the overall model is done by coordinating the sub-models and subsequent analyses, which can be partially automated. Nevertheless, every planner can use his or her specialist tool for the planning task but must connect his results to the overall factory model. Therefore, an inter-operationally between different planning tools need to be considered in the software architecture selection.

(3) Smart Experts accessible everywhere on any device

As already explained, the main idea of IFM is to create a common platform for all project participants to interact and exchange data. To achieve the overall communication between all necessary stakeholders, an implemented cloud service is used. The cloud service integrates both the factory model and the planning process to ensure a more connected and effective workflow. To secure the explained synchronized working, the platform must synchronize data from multiple sources and provide consistent, up to date information to every stakeholder. Therefore, IFM includes a centralized document management system that bundles the available information at all necessary levels of detail within in the 3D factory model. Furthermore, individual applications, so called Smart Experts, can be implemented based on the planning model. These smart experts can start can be used for example in the building stage as model overlay to the building site to prove correct building. Similar to the use of BIM models, this step enables a target-performance comparison of the virtual model and the factory currently under construction. This allows to prevent errors in the early phase and to reduce the error costs significantly. Another smart expert could be a material flow simulation based on the model details or a virtual reality process validation. The number and application of smart experts is depending on the planning case and user specific.

As an example of the usage of IFM the equipment supplier model delivery process which was implemented at the e.GO Mobile AG is presented. The e.GO Mobile AG is a young automotive start-up founded in 2015 by Prof. Günther Schuh in Aachen. The founding ide of e.GO was to produce electric small-size vehicle for less than 10.000€. Furthermore, the product design logic was changed from customer-orientated design to production-orientated design. Additionally, the factory and production planning was parallelized to the product design, leading to a factory planning of just 18 months and just two months lead time from production design freeze and first product build. The e.GO Life, a small-sized two person electric vehicle with a range of around 150 km, is the first product of the e.GO Mobile AG using an aluminum-hybrid structure. The e.GO Mover, the second product, is planned to be a partly autonomous shuttle bus for up to 25 people. The e.GO Mover is planned have a hybrid body structure of carbon and aluminum. Both, the e.GO Life and the e.GO Mover, are produced in two manufacturing and one body-shop factory in low volume in Aachen, Germany.

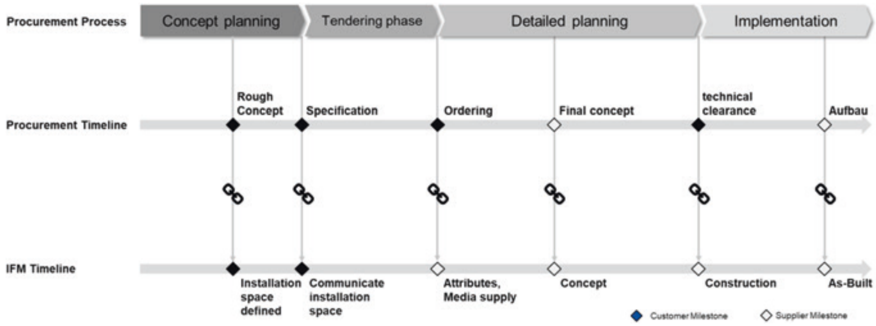

Fig. 4. Connected IFM and procurement timelines

Key to success for the e.GO Mobile AG was the fully integration of product, production and procurement processes. This connectivity was particularly crucial in the successful implementation of the change from an L6e vehicle classification to M1. Due to the digitally connected processes, changes in the product, like dimensional or material changes directly were communicated production planner. In case of dimensional changes, various measures are possible to ensure producibility, e.g. editing the assembly station design or the line side space requirement for the part's container. For material changes, existing machining capabilities and capacities needed to be checked. Nevertheless, due to the direct information and possibility to review every change, the production could quickly update their planning or hand feedback to the development team to review their planning due to restrictions in the production. In total this leaded to a reduced product and production development time, leading to a quicker time to market, by around 30 percent in comparison to automotive industry standards. A very important cooperation for the production planning were the integrated factory and procurement processes, which can exemplarily be seen in Fig. 4. A five step stage-gate process was developed by e.GO to align on the one hand factory planning and procurement milestones and on the other hand integrate the supplier data directly into the factory model. Key of the stage-gate process is the so-called Level of Detail (LoD) which define model requirements similar to deliverables in BIM. Therefore, LoD 100 to LoD 500 are indicating the degree of maturity of the digital planning status. The extension is especially used for the awarding of contracts for larger plants or for areas to be contracted externally. Each step of the stage-gate process will be explained following. Additionally, Fig. 5 gives an example regarding the model maturity at each stage.

As first step, the equipment planner starts a supplier award process, defines and specifies the available/planned space which is intended for the equipment to be purchased, the so called LoD 100 model, and provides a specification sheet for the supplier. All of these is published to selected suppliers as an Request for Quotation (RfQ). As initial feedback, the interested suppliers provide first requirements for any media supplies, bearings and other general requirements. This results into a parameterized model which is called LoD 200. After these are aligned, the supplier specifies his model and creates a first conceptual presentation of the solution of the equipment, which is called LoD 300. Based on these modes, the equipment and processes with it will be closely evaluated and validated. At the end of this step, the equipment planner finally decides on a supplier with whom he will complete the project. Following the general planning and the selection of suppliers, the supplier develops a detailed plan including a business case. In addition, the supplier creates an interface examination. This allows an examination of possible material flows or even logistics processes. The model is refined and detailed until a complete engineering representation, the so called LoD 400. Based on the engineering representation model the final order confirmation and approval for production. After the equipment is installed at the facility, a 3D scan of the finished area is created and compared with the 3D planning model of LoD 400. If the scan matches the model and any agreed changes have been implemented, payment to the supplier can be released and the process ends with an As-built model of the equipment, the so called LoD 500.

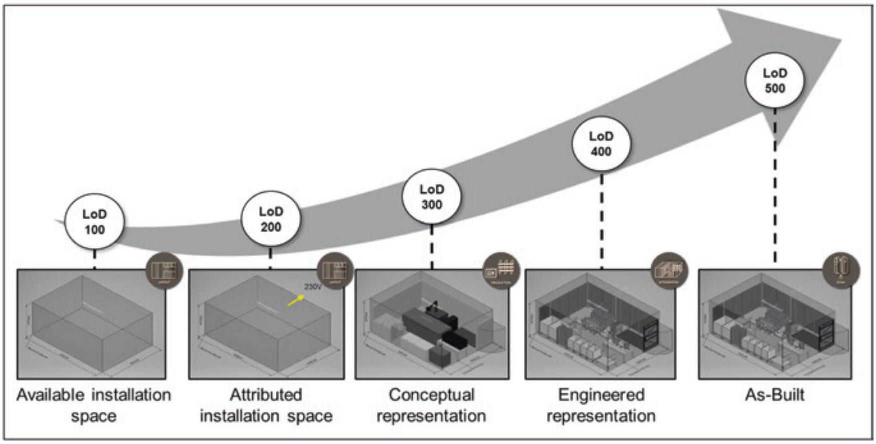

Fig. 5. IFM the five stages equipment supplier model delivery process

4 Outlook

By using integrated factory modelling (IFM) at the e.GO Mobile AG significant advancements in the area of factory planning could be achieved. A shortened planning time by 15 months as well as planning cost savings of roughly 33% in comparison to comparable projects can be named besides a higher quality of planning and accurate digital models. Nevertheless, additional functions and advancements in the methodology are possible and in research. Three major projects are shortly named:

The long-term goal should be the automation of the factory planning processes. Therefore, using methods of artificial intelligence (AI) should be considered as suitable approach for the stated goal with the digital factory model being a basis. This model already provides all required information in a machine-readable form which can be used by the algorithms of the AI. Similarly, AI can feed its results back into the digital factory model, allowing easy and efficient further use of the model.

Furthermore, it possible to integrate the so-called Generative Layout Design Approach which is based on the Aachen factory planning procedure and evolutionary algorithms. Based on the desired input parameters, a considerable number of layout alternatives are generated, and a possible solution space is defined. This space is systematically searched and automatically limited by a targeted evolution algorithm. This procedure enables to generate the best possible solution in a reasonable computing time. The rapid calculation of the evolutionary algorithm therefore ensures that changing parameters in the planning data which can be quickly evaluated and included in the calculation. This approach makes it possible to significantly reduce the planning time.

The IFM is also an important first step towards optimizing data management in factory planning. A study by Bracht stated out that a factory planner invests 23% of their time for searching information. Even if a piece of information is found, there is no guarantee that is up-to-date, complete or correct. The IFM already is provides a central platform with linked information for each object, for example the maximum permissible load of a forklift truck. Further information can be automatically added and updated using algorithms known from social media platforms. With automated information retrieval technologies combined with the central information database the value-added time of planners can be significantly increased and double efforts can be reduced.

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