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MULTI-CRITERIA DECISION SUPPORT IN CONSTRUCTION MANAGEMENT: LIFE CYCLE-ORIENTED INVESTIGATION OF THE ECONOMIC EFFICIENCY

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ABSTRACT

The focus of this paper is an efficient data usage in order to investigate the economic efficiency of a building element. Decisions in construction management are related to the life cycle of a building. In combination with numerous influencing factors there is a need for a decision support approach, which enables the user to ensure data is available and can be used efficiently to identify the best decision. To meet these challenges, this paper presents a data-based approach for combining different datasets to ensure a comprehensive base for multi-criteria decision support in construction management.

VARIANT COMPARISON IN CONSTRUCTION MANAGEMENT

Variant comparisons are permanently carried out within construction management in order to analyse and evaluate different parameter constellations. For example, an adjustment of qualities in connection with the variation of effort and cost parameters can have a considerable influence on the cost calculation or schedule planning. If the operating costs of a property are considered in conjunction with a possible modernisation of the heating system, different characteristic values for the calculation of the expected operating costs can give different or even contradictory impulses for or against an investment in a modern heating system. Variant comparisons make the variances visible and provide information about possible scenario developments in project management. In the context of the life cycle (Design, Construction, Operation and Revitalisation) of a building, parameter variations regularly affect not only one life cycle phase but have a cross-phase influence on the target parameters to be evaluated.

Construction projects are also planned, realised, operated and revitalised by a large number of construction parties throughout the entire life cycle (Figure 1). The number of participants from different disciplines implies a high degree of complexity, as different specialist information must be correlated in order to make it possible to evaluate it in a holistic way. An additional dynamic is created by the possibility of a change of the building design by the client during the realisation phase. The modification of the construction design can therefore affect various parameters and target parameters (Gralla, Lenz, 2019).

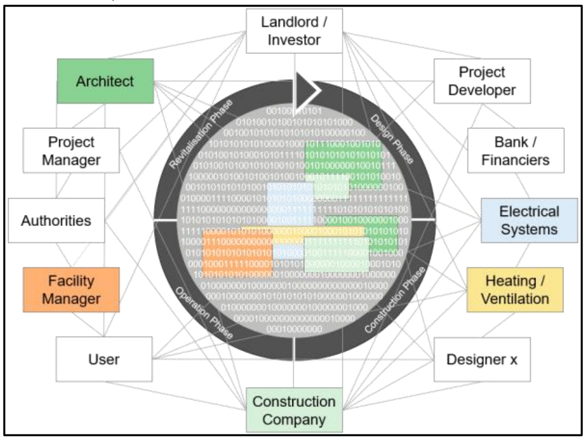


Figure 1: Project participants and influences during the life cycle of a building (Gralla, Lenz, 2019)

Multi-citeria decisions in construction management

Multi-criteria decision problems occur in situations where several criteria can have an influence on a decision and vice versa (Yu, Chen, 2010). This applies to construction project management decisions in unison. Ordinarily, it is not just a question of taking one criterion into account, but of considering a range of relevant target parameters, which may even be in competition with each other and are not easily scalable or comparable. Summarizing, the following characteristics (see table 1) are representative for multi-criteria decision problems:

Table 1: Characteristics of multi-criteria decision problems (Zimmermann, Gutsche, 1991)

Characteristic	Description	Example construction management
Multiple targets	The decision maker himself decides on the relevance of a goal for the decision problem.	**Engineer Heating**: high quality, reduced operation costs **Investor**: low invest costs, reduced operation costs, system should be sustainable **Architect**: less space for heating systems in the building
Target conflict	An improvement with regard to one objective worsens the result with regard to another objective. A meaningful criterion is needed to evaluate the alternatives.	**Performance targets vs. sustainability targets (SUT) vs. strategic targets (ST):** Low invest costs (ST) vs. sustainibility (SUT)
Incomparable units	Targets are measured with incomparable scales or in noncomparable units.	Costs for the system vs. quality units vs. performance of the system
Choosing a solution	The action alternative that the decision maker most prefers with regard to all objectives is selected. If the set of action alterniatives is finite, the best alternative is selected. If the number of action alternatives is not explicitly defined, the best action is found by calculation.	Decision support system, decision maker can adjust different influences by rating them, e.g. investor rates construction costs as more important than operation costs, because the user has to pay them.

Within the construction industry the Building Information Modelling seen as the main digitization driver. "Building Information Modelling (BIM) is a planning method in civil engineering that involves the creation and management of digital virtual representations of the physical and functional properties of a structure. The building models provide a database of information about the building in order to provide a reliable source for decisions throughout the entire life cycle of the building; from the first preliminary planning to its dismantling"(Egger, 2013, p. 18).

Scheduling aspects are taken into account as time or effort values with the BIM-Model respecting its components as the fourth dimension. For this purpose, the BIM-Model is linked to the corresponding schedule. The virtual components of the BIM-Model are linked to schedule processes, which allows the construction process to be simulated. The granularity of the simulation and visualization is variable so that a wide variety of schedules can be linked to the BIM-Model. Furthermore, the virtual components can be variably combined into groups and assigned to different schedule processes (Weist, 2019, p. 23). For the consideration of costs, the pricing and thus cost-relevant information is combined with the objects of the BIM-Model in the fifth dimension. After consolidating the objects with individual items of a bill of quantities, a model-based cost determination can be carried out on the basis of the linked information, such as wage, material, equipment costs, etc. The linking of the BIM-Model to a set of service specifications is also variable, so that several can be assigned to one item of service specifications (Gralla/Lenz, 2017). The linking of scheduling and cost relevant aspects to the specific BIM-Models is done, because the originally scheduling and cost calculation is mostly done by other teams which work in specific software which should be BIM capable. By that, the created calculation or scheduling is then linked with the related objects within the BIM-Models. By that, a more dynamic process occurs because the modelling teams works simultaneously on the BIM-Model as the calculating team works on the related cost calculation and the scheduling team creates the schedule. This leads to a more efficient and agile BIM process.

By synthesizing scheduled, cost-relevant and further information with the geometric information, target/actual comparisons, payment plans, performance reports as well as budget and execution quantity controlling and many other evaluations can be carried out on a model-based basis. The use of the BIM-Model as a central source of information and knowledge or database over the entire life cycle of a property is the main difference to conventional project management. All the necessary information specific to the respective application is available, so that evaluations can be carried out in real time on the basis of the classic construction business key figures such as quality, costs and time. (Weist, 2019, p. 24).

Regarding this, all information which are necessary for the decision-making can be considered in a BIM-Model. By that, also the interdependencies between different criteria which are taken into account in the BIM-Modell can be utilized for the decision-making process. For example, the input and output KPI's of a heating boiler can be considered within the BIM-Model for simulation purposes. Changing the given KPI's will affect the costs and schedules within the different life-cycle phases of the building. Therefore, all of the data stored in the BIM-Model can be changed and will occur other results which have to be taken into account in the decision-making process. Correspondingly, there is potential by using BIM-Models as a database for multi-criteria decision support.

Complexity and potential of multi-criteria decisions

For multi-criteria decision problems to be better addressed and thus also solved, they must first be classified. With the help of this classification, targeted measures or methods can then be used to solve the problem more efficiently. In this context it is useful to describe multi-criteria decision problems as complex or complex system or complex construct (Bohne, 1998).

Complexity is described by numerous connections of individual elements in a system that interact with each other or exchange information. Even though such a system can also be called a complicated system, the two terminologies differ in the number and characteristics of the respective connections and interactions. If a complicated system has many connections and interactions that are still manageable, a complex system exceeds this number and may no longer be completely comprehensible as a system. This means that to get an overview of a complicated system is to a certain extent very difficult, but still possible, while a complex system cannot be analyzed and understood without assistance tools. (Schuh, 2014, Ulrich, Probst, 1988, Klir, 2001). (Mitchel, Newman, 2001, p. 1) (Saurin, Rooke, Koskalin, 2013 p. 5825) (Snowden, Boone, 2007, p. 69–76.) (Foster, 2005, p. 874) (Schuh, Gottschalk, 2008, p. 432).

Transferring this definition to the solution of multi-criteria decision problems, it is possible to transfer methods for the solution of complex problems and thus achieve a satisfactory result more efficiently. Potential of variant comparisons in different life cycle phases, the interactions among each other (cross-life cycle), also the potential of a decision taking into account real all criteria (currently not used), regarding qualities, costs and deadlines (construction operation).

A collection of several, structurally different, but largely identical solutions is also known as product line. Each point of variation can be realized by a set of features whose cardinality multiplicatively enters into the number of possible occurrences of the product line. With eight variation points and two possible related implementations, up to 256 possible product characteristics are already created in this way. Consequently, it is extremely challenging to create and test the different variants of a product line without automation and reuse. Furthermore, the multiplicative relationship between the costs for the selection and integration of features asymptotically always exceeds the additive connection between the total costs and the realization of separate features. Combinatory software synthesis is motivated by this cost composition. Independently implemented features in the form of a component repository are assumed and their selection and composition are automated by an algorithm. (Wenzel et al., 2019)

It is usually difficult to map complete systems for decision making taking into account all the framework conditions and details. Therefore, it is necessary to identify the relevant areas and criteria of the variant to be considered and to map and evaluate the variants with respect to these criteria, (Winkels et al., 2018) has already shown that an automated composition of solution alternatives is possible. Although the complete life cycle was not considered, it turned out that this is not necessary if the system can work with sufficient information. In the cited paper, adaptations of existing systems were analysed. In case of a completely new system from scratch, it would certainly be harder because of less restrictive conditions and therefore a bigger solution space. The procedure is nevertheless transferable to other use cases, which was shown in (Winkels, 2019, Graefenstein, 2019).

USING SOFTWARE SYNTHESIS METHODS FOR MULTI-CRITERIA PROBLEMS

In order to be able to map the variability and the numerous different configuration possibilities the information technology approach converts the planning task into a feature model. Feature models are originally a representation of all occurrences of a software product line (SPL). An SPL is a collection (or family) of related programs that are based on a common software kernel but differ in features. A “feature” is defined as a “salient or distinguishable user-visible aspect, quality or characteristic of a software system” (Winkels et al., 2018). Feature models are visualized through feature diagrams and used throughout the product line development process.

The model defines the features, their characteristics, as well as their dependencies, which are reflected in the diagram. In addition, the models can have other constraints, which can be represented in additional documentation (tables, etc.). A concrete incarnation of a member of an SPL is called a feature configuration. A configuration is only allowed if it does not violate any constraints described in the model. The concept of the software product lines has been adapted to the present work and its underlying scenario. It will be introduced and used as a production product line (PPL) at this point. In our scenario, different variants of individual components of the material flow are considered as features. Different transport systems for example represent different factory features. Configuration is allowed if at least one feature is selected from all the required components and global constraints such as the budget limit are not violated. Figure 2 shows a possible portrayal of such a feature model based on an example scenario that will be discussed in more detail later.

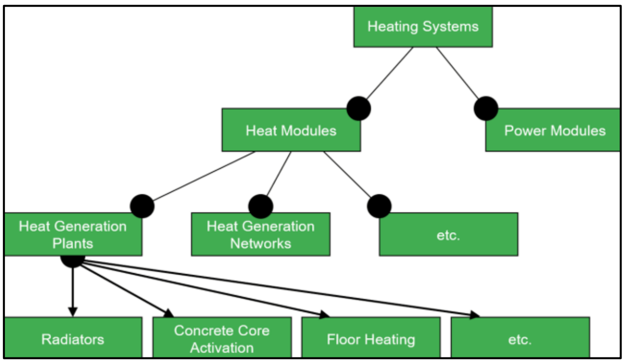


Figure 2: Example of a Feature Model

If one wants to generate and evaluate solution alternatives automatically, it is necessary to provide the corresponding software system with sufficient information about the variants to be generated. This means, for example, that an information "heating boiler" already contains information like maintenance intervals or suchlike.

With this and further information from other related modules, it is possible to check whether target criteria such as heating capacity or energy consumption are met. The necessary information must be available beforehand so that a complete check is possible. If this is not the case, this information would have to be added to obtain useful results. If this is the case, such a check can be performed algorithmically. Several academic and commercial approaches already exist for this purpose, such as the Z3 Constraintsolver from Microsoft (Moura, Bjorner, 2008, p. 337 – 340). The advantage of this is that any gaps in the model's database can be detected and that several phases of the life cycle can be run through with varying data bases. For example, the existing data for installed heating lines or pumps in the construction phase may be different from that in the operating phase of the building. This would also result in different framework conditions, which can be taken into account when examining possible solutions.

This can be realized as a modular approach (Figure 3) analogous to the one in “Automatic composition of rough solution possibilities in the target planning of factory planning projects by means of combinatorial logic” (Winkels et al., 2018). Different (heating) systems are represented as a module with different inputs and outputs. If a module gets information from another module that already has certain values like pipe diameter or pumping capacity, it becomes clear if the new system can be

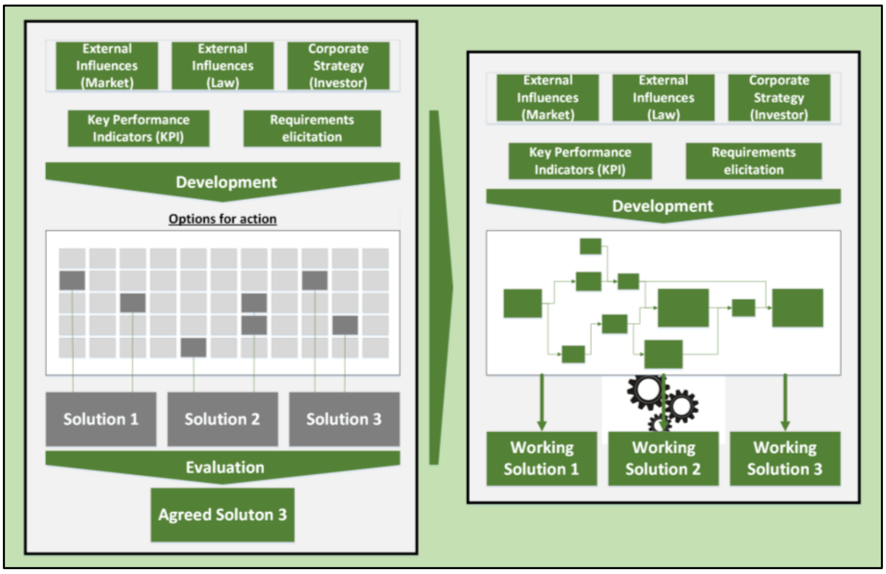


Figure 3: Classic way and automated way of formulating solutions for actual planning processes (Winkels et al., 2018)

composed consistently. Incompatible modules can be identified directly and the solution variant which contains such an incompatible module is not considered further. At the same time effects on the evaluation criteria can be specified directly in the modules. This way it can be determined which costs the use of a certain component would cause. With an automated generation of complete solutions, the total costs can be calculated immediately. As described in Winkels et al., 2018, the synthesis framework "Combinatory Logic Synthesizer" is used for this. An exact description of the underlying algorithm can be found in the paper.

The decision for one of the generated alternatives must still be made by the responsible persons (Figure 4). A fully automatic multi-criteria decision is only possible if the criteria have been weighted beforehand (for example by stating that low costs are more important than high space consumption). By such a procedure described above, however, the basis for discussion and decision making is much better and the solution finding much faster. With these generated solutions you get emotionally neutral, data-based solutions that really work. Each participant can see the characteristics and consequences of each individual decision in this way.

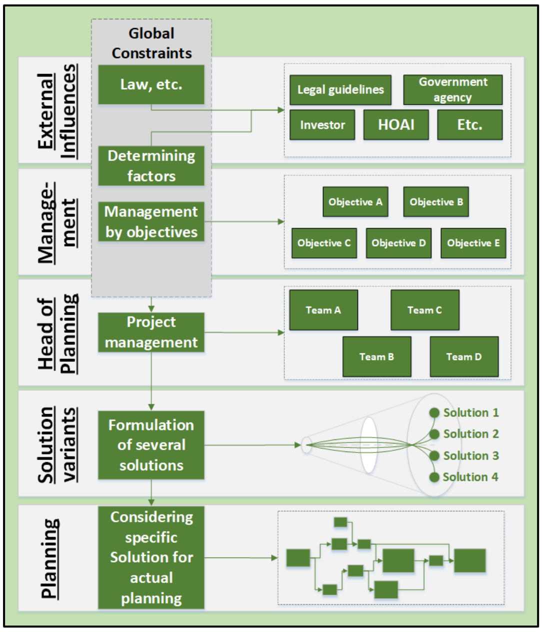


Figure 4: Stages involved in the solution formulation process (Winkels et al., 2018)

DECISION-MAKING PROCESS IN CONSTRUCTION MANAGEMENT STATUS QUO

Decisions based on manual processes are often not made under consideration of all criteria. Accordingly, a certain inefficiency can be identified in the processes leading to a decision as well as in the quality of the decision itself. A decision-making process can be introduced in different phases with input and output. The approach used in this paper is differentiated in four phases, the observation phase for the recognition of a demand for a decision, the analysis phase, to analyse if the decision is necessary, the planning phase, to plan the decision respective developing the basis for the decision by taking the influencing factor and all criteria into account and the decision phase, where a decision for a variant is made.

The output of the process is differentiated in output pre-decision (before the decision is made) as a basis for the decision and post-decision, which can be used in a kind of feedback-loop as more knowledge to improve the decision basis for further decisions in a similar form. The level of criteria is increasing during the decision-making process and because of that the complexity also rises (Figure 5).

Especially the existence of incomplete information is the reason therefor, that all parties concerned with decision-making problems in the construction sector are faced with uncertainty are challenged. It can be assumed, moreover, that this could reduce the parties' cost risk for the post-award phase. For the assessment and evaluation

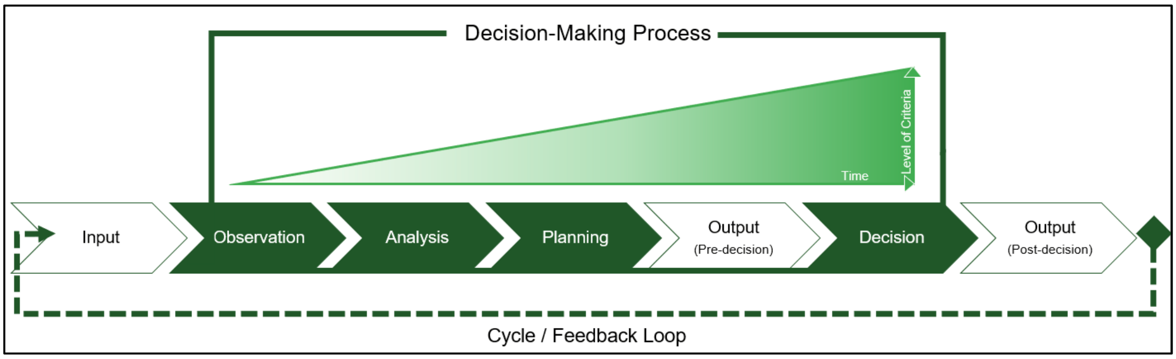


Figure 5: Decision-making process vs. level of criteria

of probabilistic data, decision-theoretical tools are available which make objectively comprehensible decisions possible. However, the decisive basis for decision-making is the quantification of the risk-benefit attitudes of the decision-makers, which can be achieved by evaluating their risk-benefit functions (Werkl, 2013).

Within the framework of decision theory, an approach is developed to find the theoretically correct choice for decisions under uncertainty, which best corresponds to the preferences of the decision maker and thus maximizes his benefit. In construction practice, decisions are mainly not made on the basis of deterministic parameters, which means that they are based on probabilities (Heck, 2004).

APPROACH FOR DIGITAL VARIANT COMPARISONS IN CONSTRUCTION MANAGEMENT

The advantages of digitalization in the construction industry create enormous potential, such as new marketing opportunities, more efficient use of buildings in the form of new business models or ensuring the best decision for a particular application. These can be of various kinds and can promote the achievement of various target definitions.

Therefore, an efficient use of data in connection with automatic data analysis procedures with focus on decisions in construction management is elementary. These approaches can significantly simplify cross-disciplinary collaboration through the possibilities of combinatorics or synthesis of the data structures of different disciplines, generate a holistic knowledge base for decision support, increase the ability to make forecasts and thus maximize speed and efficiency (Lenz, 2020).

The value of data for variant comparisons

Data as source for decision-making processes, e.g. for the use case "Life cycle-oriented investigation of the economic efficiency of heating systems" is characterized by multidimensional influence factors, which are leading to a high complex decision-making situation.

The following table summarizes a variance of possible influencing parameters, as input data for the decision. Different data which can affect the decision are separated in categories. The same category can contain different Data ID's which describe the properties of a data respective criteria. Furthermore, the different Data ID's contain data values which can change due to different requirements. All of the data values will affect the decision-making process in different peculiarity. E.g. the building orientation (Data ID in first row) will affect the necessary amount of heating load because related to the building orientation the solar radiation can increase or lower the temperature within the building. Furthermore, the building soil (Data ID in second row) gives information if a geothermal heating is applicable or not, which will influence the decision making in many cases.

Table 2: Input data Use Case Heating System

Data Type	Category no.	Category name	Data ID	Data Value
INPUT	1	Location of the building	Building orientation	Amount of the heating load
INPUT	1	Location of the building	Building soil	Geothermal heating applicable
INPUT	1	Location of the building	Building environment	Space for external systems
INPUT	1	Location of the building	Building Position	Environment temperature
INPUT	2	Building dimensions	Size technical room	Dimension of the heating system
INPUT	2	Building dimensions	Location technical room	Heat distribution network
INPUT	3	Component dimensions	Surface Areas	Floors
INPUT	3	Component dimensions	Surface Areas	Walls
INPUT	4	Building components	Competing systems	Photovoltaic system
INPUT	4	Building components	Competing systems	Solarthermie
INPUT	5	Dimension of the heating system	Average heat transfer coefficient	Value
INPUT	6	Dimension of the heating system	Thermal bridges	Value
INPUT	7	Dimension of the heating system	Temperature adjustment factor	Value
INPUT	8	Air exchange	Manual type	Windows
INPUT	8	Air exchange	Automatic type	Ventilation system
INPUT	9	Sustainability	Primary energy demand	Value
INPUT	9	Sustainability	Primary energy resource	Gas etc.
INPUT	10	Development of operating costs	Primary energy resource	Evolution of costs
INPUT	11	Purpose of use of the building	Type of use	Temperature
INPUT	12	Period of use	Life cycle of the system	Years
INPUT	13	User requirements	Maintenance intensity	Low etc.

These data are intended to form the basis for the subsequent development of a best practice process for digital decision-making on an option.

Best practice process for digital decision-making on an option

In order to use the developed input data for specific projects and related decision-making processes, it must be made more operational. For this purpose, the data basis is transferred into a process model which describes the process of decision-making in a more detailed way by regarding how the data is used for project management purposes. Although the structure of the decision process in Figure 6 is shown as a phase model, a modular approach is chosen for the detailed description and operationalization to allow flexible adjustments during the decision process. The process is structured in such a way that all data and input parameters from table 2 are first compiled in modules. Each category in table 2 is assigned to one mod-

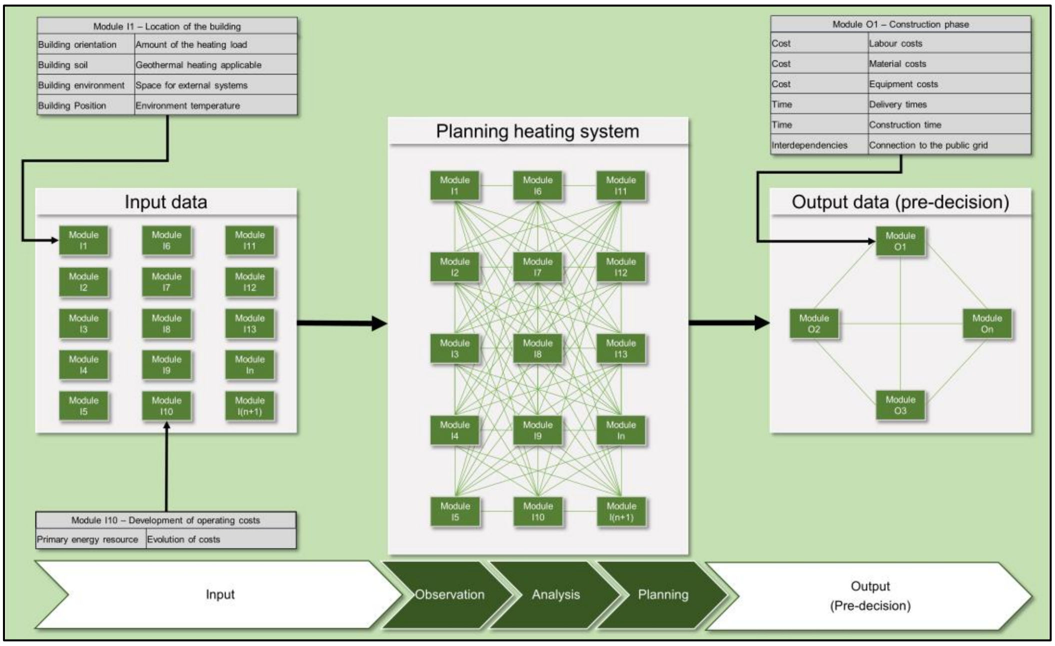
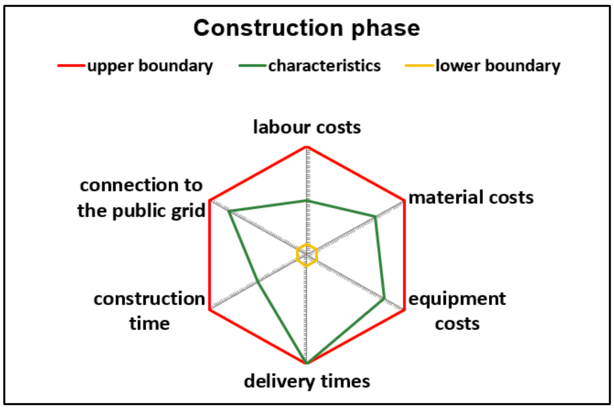


Figure 6: Modular-Decision-Making-Workflow (MDMW)

ule, whereby the number of the given category is congruent with the number of the allocated module. The data ID's and the data values are stored within the respective module. In the input phase, all parameters to be considered are first compiled. Within the observation phase, the input parameters are checked and analysed for consistency and information content. If consistency is ensured and information content exists, the data is analysed in the analysis phase. The requirements, objectives and interactions of the different parameters are determined and evaluated in the planning phase. Figure 6 shows the complexity and interdependencies of the investigated input data within the phases of observation, analysis and planning. Subsequent to the planning phase the generation of output parameters is carried out. These contain e.g. information on costs, time, quality and interactions. The information thus obtained represents the result of the observation, analysis and planning phase. The output data are also presented as modules, whereby these are coherent with the life cycle phases affected by the decision problem



to be investigated. By doing so, the stakeholders assigned to the respective lifecycle phases can view the information that is decisive for them.

Figure 7: Decision criteria during Construction phase

Accordingly, the created modules contain different information, which still interact with each other. If only one life cycle phase is considered, the interrelations and interactions of the information of an output module can be visualized in a spider diagram. Accordingly, Figure 7 shows examples of the information of the construction phase that is relevant and necessary for the decision.

In some cases, it may be sufficient to make a decision based solely on the information of one life cycle phase. If, however, various stakeholders have to be taken into account, different goals arise which are inherent in the system and can lead to different decisions, but which do not take into account an overall goal. In this case it is crucial to integrate all criteria and information into the decision process. In the present case, therefore, modules for the respective life cycle phases within the output data were created in order to create the necessary transparency for all project participants and thus make the goals and the different stakeholders comprehensible. If this information and requirements are taken into account, complexity inevitably increases.

Best practice process for digital decision-making on multiple variants

However, in order to achieve a holistic evaluation and resulting decision, the output information of the associated life cycle phases must be linked together. A coupled view also creates transparency for all project participants, so that the requirements and weighting of output parameters of the various stakeholders becomes comprehensible. For example, an investor who will focus the weighting on a cost-effective installation of a heating system can be sensitized to the possibility of reducing operating costs. Table 3 shows the different life-cycle phases which are described as categories. All of the data are output from the decision-making process and carry-on different data ID. These can be separated in cost, time, quality and interdependencies. Furthermore, the specific Data ID can contain different Data values which has to be considered in the decision-making. For example, Data ID "Cost" within the category name "Construction phase" contains three types of cost values, which are regarded as Labour costs, material costs and equipment costs.

Table 3: Output data Use Case Heating System

Data Type	Category no.	Category name	Data ID	Data Value
OUTPUT	1	Construction phase	Cost	Labour costs
OUTPUT	1	Construction phase	Cost	Material costs
OUTPUT	1	Construction phase	Cost	Equipment costs
OUTPUT	1	Construction phase	Time	Delivery times
OUTPUT	1	Construction phase	Time	Construction time
OUTPUT	1	Construction phase	Interdependencies	Connection to the public grid
OUTPUT	2	Operation phase	Cost	Labour costs
OUTPUT	2	Operation phase	Cost	Material costs
OUTPUT	2	Operation phase	Cost	Equipment costs
OUTPUT	2	Operation phase	Cost	Consumption costs
OUTPUT	2	Operation phase	Time	Delivery times
OUTPUT	3	Revitalisation phase	Cost	Labour costs
OUTPUT	3	Revitalisation phase	Cost	Material costs
OUTPUT	3	Revitalisation phase	Cost	Equipment costs
OUTPUT	3	Revitalisation phase	Cost	Waste disposal costs
OUTPUT	3	Revitalisation phase	Quality	Sustainability
OUTPUT	3	Revitalisation phase	Time	Dismantling time

Figure 8 illustrates an example how the consideration of different objectives in the affected life cycle phases could increase the decision-making problem. In this purpose the weighting of decision criteria has a tremendous impact on the decision.

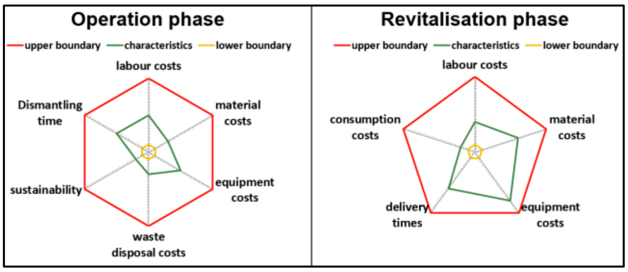


Figure 8: Decision criteria across life cycles

Considering the complete lifecycle of a building the complexity of a decision-making process will strongly increase. However, the given interdependencies of multiple criteria within different lifecycles will become obvious which increases the transparency for all participants over the whole lifecycle. The creation and use of a modular decision workflow under consideration of Building Information Modelling methods brings the advantage of model-based variant comparisons in conjunction with flexible variation of decision-criteria over the lifecycle of a building. Furthermore, by using different data within a modular approach the data is more formalized and thus automated in a flexible way. By that, multiple variants can be generated and evaluated in an automated way by the algorithm itself under consideration of weighting of different criteria. Therefore, a multidimensional decision-making process becomes more efficient and reliable whereby the complexity becomes manageable because every stakeholder and their point of view and decision criteria was taken adequately into account.

CONCLUSION & OUTLOOK

To address the tension between autonomous systems and human decisions, artificial-intelligence-based methods and information technology could be combined with the strengths of human decision-making. Accordingly, an automation of simple decision processes in the sense of recurring facts (compliance with standards and laws or similar) could be realized. Further steps can be identified in an extended, efficient decision support for humans in complex situations and their interdependencies with the other disciplines. The use of learning systems to generate synthetic training data for the application of machine learning methods for adaptation planning with the focus on the factory building could be a gain in the context of shortening planning processes. By forecasting possible implementation variants, the planning processes of a necessary structural adjustment could be anticipated and automated (e.g. building autonomously triggers an order for the required building material) and the resulting planning, decision and also implementation times could be shortened (Lenz, 2020).

If the numerous stakeholders are taken more into account, automated generation of variants based on the preferences of the respective stakeholders could be pursued. By formulating stakeholder-related profiles, different solution variants can be automatically generated which can be directly compared with each other. On this basis, aggregated variants can be created that show the greatest possible intersection of the decision criteria of the individual stakeholders. If the individual weightings or the deciding power of the respective stakeholders are also considered, a solution variant can be generated which takes all participants with their specific preferences into account. The basis for discussion is then already quite sophisticated and takes into account the individual stakeholders according to their influence and planning focus. This way the generation and decision for a solution variant which satisfies all parties involved can be supported.

In the near future, the decision-making process could evolve even further towards automated solutions. AI based on machine learning could be used to observe human decision making and thus adapt it later. However, this would require large amounts of observable and well documented decision-making processes.

It would be necessary that all decision-relevant factors are mapped in a comprehensible way for the AI. Often, however, people make decisions based on their experience, or draw on other more subjective and undocumented factors. Since objective and complete databases are therefore not available for complete decision making, the combination of human and machine components in decision making is currently still the best alternative.

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