Change Management Concepts for Structural Design in Early Planning Phases

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Abstract. Applicability and efficiency of a building design is significantly influenced by the supporting structure. Thus, a successful planning necessitates the integration of the structural engineering perspective in early phases. Additionally, the common design process is characterized by change requests that provoke interdisciplinary planning conflicts and inappropriate designs. To meet these challenges, intelligent substitution models for preliminary structural design are developed that are based on the application of engineering expert knowledge. Two methodologies are introduced for the management of design changes that are premised on the fuzzy logic-based formalization of the applied knowledge. For typical and common changes during the process, fuzzy requests are realized through temporary fuzzy sets that allow the finding of compromise solutions. Impact assessments for modifications of completed designs are enabled through extension of the applied inference systems. The presented concepts facilitate a decision support for change management and a resulting optimization of the design process.

1. Introduction

In early phases of the building planning process, the design is essentially based on creative and functional considerations. Hence, for structural assessments only few rough planning principles are allowed that commonly are simplified formulae and especially the expert experience of the structural engineers. Nevertheless, an early integration of essential structural information is of high importance for a successful design of buildings. The structural parameters are deducted from the basic specifications like the floor plan, the usage category and the building equipment that provide only few boundary conditions for the following preliminary design. Anyway, in this phase significant structural decisions are taken that entail a high influence on the further project processing and building construction (Zhang et al, 2018). The factors time and costs are significantly affected by the structural design and key aspects in the field of public construction and large-scale investments (Kim et al, 2015). Consequently, an integration of the structural design perspective in earliest possible planning phases is highly advisable (Schnellenbach-Held and Hartmann, 2003). For this purpose, the interdisciplinary collaboration of all involved planners is necessary at the same time (Oh et al, 2015; El-Diraby et al, 2017). This demands the introduction of applicable structural engineering expertise in the preliminary design stage. In addition to a useful formalization of the knowledge, its generation usually requires extensive structural analyses and simulations (Liu et al 2018). The resulting systems for the support of design decisions need to process and recommend structural solutions based on few specifications and vague parameters (Schnellenbach-Held and Albert, 2003). For this purpose, intelligent substitution models are developed that are based on development-level dependent fuzzy knowledge bases for structural design. The new approach utilizes the common intuitive engineering expertise that necessitates a specialized system of development levels as well as an applicable knowledge formalization with fuzzy logic (Steiner and Schnellenbach-Held, 2018).

In addition to the challenge of early interdisciplinary planning, the preliminary design of buildings is characterized by design modification requests from the involved planners. In principle, two differentiable kinds of demanded model parameter changes are identifiable. Typical and common adjustments occur during the design process and modifications of a completed design appear after the regular process. In the field of computer-aided decision-making, such revisions frequently provoke conflict situations that result in inappropriate designs. The ability of modification handling is realizable through applicable change management concepts. For this purpose, two basic methodologies are developed that provide a support of the decision-making process for design modification requests. For conflict situations that are induced by typical and common changes and occur during the design process, the concept of fuzzy requests allows the detection of compromise solutions. Through enhancement of the inference systems that are included in the substitution models, an impact assessment is enabled for design modifications appearing after the regular process. These methodologies enable an optimization of the building planning process through an advanced decision support. In this paper, the change management concepts for structural design in early planning phases are presented that allow the consideration of modification requests in the early design process.

2. Structural design in early planning phases

For an integration of the structural engineering perspective in early planning phases of the building design process, intelligent substitution models are developed that are based on development-level dependent expert knowledge. The applied knowledge is assigned to a specialized detailing system that consists of identified development levels for the preliminary structural design. Regarding the development of a supporting system, level dependent fuzzy knowledge bases for structural design are formulated and generated to include applicable engineering experience. For an imitation of the related decision-making process, intelligent substitution models are developed that are premised on the inference of the fuzzy knowledge bases. By means of the resulting systems, a decision support for structural preliminary design (pre-design) is realized. This enables the integration of the structural engineering perspective in early planning phases and thus an associated optimization of the building design process (Steiner and Schnellenbach-Held, 2018).

2.1 Adaptive levels of development for structural pre-design

In the common process of preliminary design and early assessments of supporting structures, the applied engineering knowledge and experience is assignable to typical levels of detailing and development (Maier et al, 2017). For a structural design, important information is premised on criteria like usability, load carrying capacity and cost efficiency of a load bearing system. Based on analyzed requirements for the included information and comprehension for structural design, an applicable configuration of Adaptive Levels of Development (ALoDs) and included parameters is developed for building models. In addition to adaptivity needs for multidisciplinary building design scenarios (Schnellenbach-Held and Steiner, 2019), the specialized perspective requires a new level system besides the numerous existing LOD specifications. The resulting level system (see figure 1) includes a basic understanding of structural engineering as well as related parameters that are necessary for the representation and further development of a supporting structure. For this purpose, five ALoDs are identified to represent applicable model states that are based on the pragmatic structural engineering comprehension. These levels are connected through transfer functions that increase the development status of the building model. The associated necessary determination of additional information is performed by the intelligent substitution models for structural pre-design that represent the implementation of the transfer functions (Steiner, 2018).

In the beginning of the design process the “ALoD 0” is defined as blackbox that provides initial parameters for global information and environmental conditions as well as the external model dimensions. Based on the ALoD 0, the subsequent floor plan development of the architect or a construction grid estimation through the substitution model “grid” are enabled. The architect-driven development results in the geometrical specification of the entire building model that is content of the “ALoD 1” enclosing the complete geometries of all components. Based on the geometric information, the common idealization of load-bearing elements is realizable through the positioning method. Alternatively, the idealized elements are inserted in the context of the grid estimation that is based on structural engineering knowledge.

In both ways, common structural positions are integrated into the model as the typical idealized elements in “ALoD 2a” that are the basis for the assessment and the design of structures with engineering expert knowledge according to conventional calculation approaches. Determination of the suitability of the structural positions is performed by the substitution model “possibility” that simulates the evaluation of structural designs based on engineering experience. For the resulting expert rating in “ALoD 2b”, the possibility value is introduced that features a value range from 0,0 for “not realizable” over 0,5 for “possible” up to 1,0 for “optimal” designs. The resulting formalization of structural assessments allows the decision-making support for the design process and for the management of design modifications. The characteristic structural parameters of the selected design are determined by the substitution model “pre-design” that finalizes the preliminary dimensioning of the supporting elements. These conclusive pre-design specifications are content of the “ALoD 3” that comprises the preliminarily dimensioned structural solution and allows further analyses of the building model (Steiner and Schnellenbach-Held, 2018).

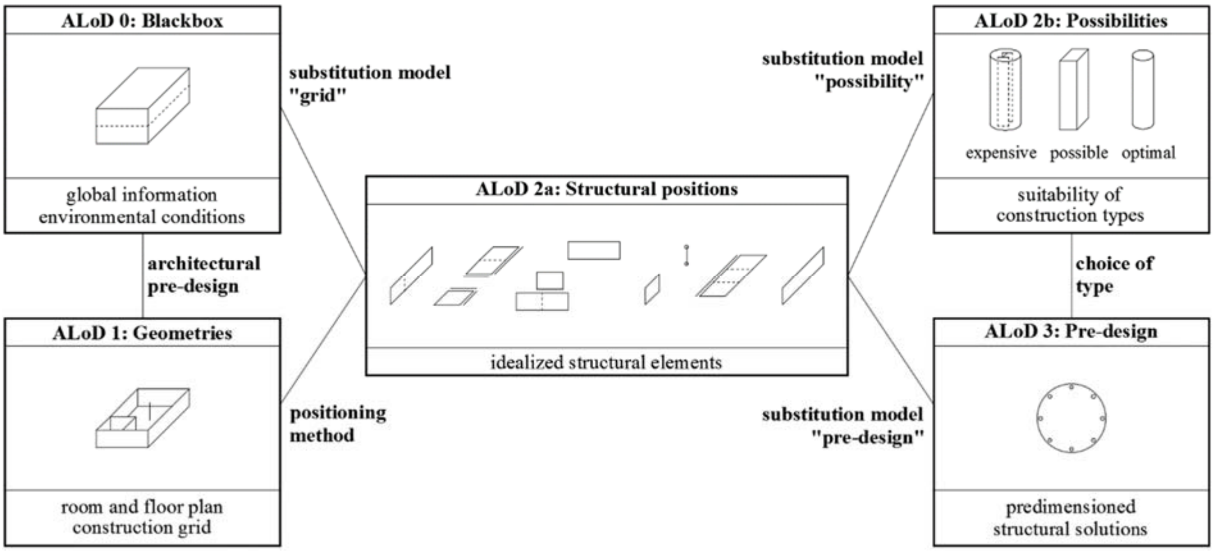

Figure 1: Development system for structural design based on Steiner and Schnellenbach-Held 2018.

2.2 Intelligent substitution models for structural pre-design

The concept of the developed intelligent substitution models is based on the application of engineering experience for structural preliminary design. Formalization of this expertise is realized using fuzzy logic-based methods that allow the application of expert knowledge and rule-based inference systems. Featuring extraordinary generalization abilities, these systems enable the imitation of human problem-solving mechanisms and reasoning competences even under most complex conditions (Steiner and Schnellenbach-Held, 2017). In the field of artificial intelligence (AI), fuzzy logic inference systems are common and well-known solutions for the simulation of decision-making processes (Schnellenbach-Held and Steiner, 2014).

Using the fuzzy approach, ALoD-dependent fuzzy knowledge bases are developed. They include applicable expert knowledge for the assessment and the structural design of load-bearing elements that is based on binding codes and directive standards as well as engineering knowledge, experience and competence. Following the formalization approach, the resulting rule bases are phrased in the Modus Ponens "if premise (lower ALoD), then conclusion (higher ALoD)" that is transparent and easy to understand (see table 1). The related decision-making processes are realized with functional TSK fuzzy inference systems that enable the evaluation of parameters for the model development through application of the engineering knowledge (Steiner and Schnellenbach-Held 2018).

Table 1: Exemplary rule for the inference systems of the substitution models

Rule		Parameter		Fuzzy set	Crisp value	ALoD
IF		Position	=		Single-span slab	ALoD 2a
	AND	Useful load	=	"small"	2,00 kN/m²	ALoD 2a
	AND	Height	=	"small"	0,20 m	ALoD 2a
	AND	Length	=	"small"	3,00 m	ALoD 2a
THEN		Possibility	=	"optimal"	1,0 –	ALoD 2b
	AND	Concrete class	=		C20: Smallest possible	ALoD 3
	AND	Reinforcement	=	"small"	6,79 kg/m	ALoD 3

Generation of the knowledge is based on parameter studies for the structural design of typical idealized positions of load bearing elements (ALoD 2a). For the configuration of the studies, adequate value boundaries and a sampling of the parameters are determined through common engineering experience. Based on the satisfaction of the required limit states according to Eurocode, the usability (ALoD 2b) and the design values (ALoD 3) of a structural element are determined. In the process, the qualification of the elements is formulated as "possible" for plannable elements and "not realizable" for infringing structures. Further determinations of the possibility are based on expert knowledge for structural ratings. As large numbers of realizable solutions occur for certain boundary conditions, optimization tasks are performed as search for the minimal approximate realization effort. The results are expressed as expert rules that are verifiable with common engineering experience. Using the additional knowledge for structural assessments, the possibility values are updated and thus a comparison basis is established for design choices and the change management. Based on the combination of the possibility progressions and the expert assessment knowledge, superordinate rules are identified that allow an estimation of construction grids with applicable and optimized structural positions (ALoD 2a). Finally, the rule bases of the inference systems are derived from the incrementally approximated functions for structural design. With the resulting substitution models, a reliable decision support is realized that enables an integration of the structural engineering perspective in early phases of the building design process (Steiner, 2018).

3. Fuzzy requests for compromise solutions

Typical and common design changes occur during the design process. Intended by the involved planners in the preliminary design of architectures, they often provoke conflict situations between the different planning disciplines. Using computer-aided decision-making processes, such changes provoke improper results that occur due to effects on assessments of the other planners. In the common real design process, these change requests are not formulated as a categorical modification by a certain value of an exact amount, but rather as an allowed fuzzy range of adjustment. Providing that these ranges indicate the preferences for different modification values, this formulation enables a compromise finding for the change induced interdisciplinary planning conflicts (Steiner and Schnellenbach-Held, 2018).

3.1 Formalization of fuzzy requests

As example, the structural engineer formulates a request for the change of a girder height using sharp values (see figure 2). The requested modification could be a crisp height increase from 60 cm to 80 cm in order to save reinforcement. As this change gives only few opportunities, there is a high risk of rejection of this request by the architect, possibly because the required clear room height is not achieved. Conversely, the request can be expressed with fuzzy values that rise from 0 at 60 cm to 1 at 80 cm. The assessment of the architect can be phrased analogously with involved preferences like falling from 1 at 60 cm to 0 at 80 cm. In doing so, the detection of an appropriate compromise solution is much more likely, as much more opportunities are given.

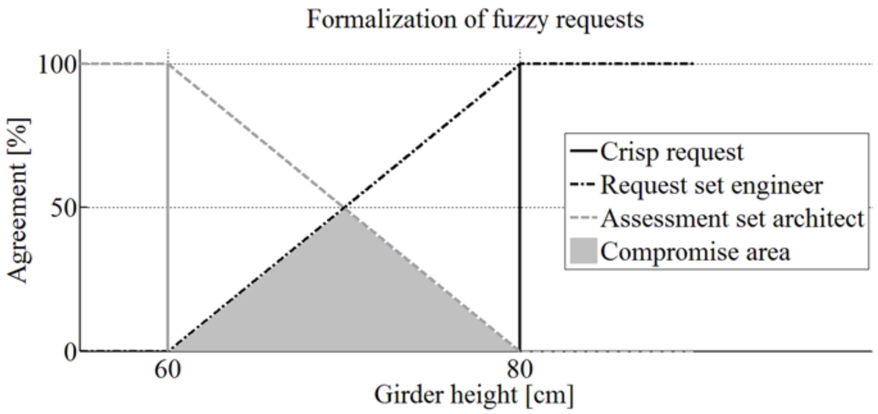

Figure 2: Formalization of change requests with fuzzy sets

The required integration of progressions in the design priorities of the different disciplines can be realized through the request formalization with fuzzy values. In accordance with ALoD 2b, the membership values of these sets conform to the possibility values that range from 0 for "unsuitable" over 0.5 for "possible" to 1 for "optimal" ratings. The resulting formalization of fuzzy requests through possibility progressions includes the allowed value ranges for the design modification as well as related preferences of the planners. The resulting concept of "fuzzy requests" is a promising approach for the management of common changes during the preliminary design of buildings. A practice-oriented modeling and support of frequently occurring interdisciplinary planning conflicts are enabled by the included computer-aided decision-making processes. This can significantly contribute to the perpetuation of continuity and integrity of the design process in early phases.

3.2 Compromise solution detection

The consideration of fuzzy requests within the developed ALoD-system and substitution models as well as the resulting complementation of the compromise finding require associated analyses based on fuzzy parameters. The extension principle according to L.A. Zadeh (Zadeh, 1965) represents a theoretical basis for the generalization of arbitrary functions to fuzzy input parameters. Considering a function with a fuzzy set as delivered argument, this principle allows the determination of membership progressions for the functional fuzzy parameters. The application of α-cuts has been proved to be helpful for the computational implementation of the extension principle (Kaufmann, 1985). For a fuzzy set, the α-cut is a crisp set of all elements that feature a membership degree μ in the confidence interval, where $\mu \geq \alpha$ is satisfied. Thereby, a discretization of the fuzzy sets is enabled. For a function with fuzzy input parameters, the determination of membership functions for result variables proved to be problematic when using α-cuts, if non-monotone mapping operators are used or the input variables are influencing each other. Therefore, various methods have been developed to specify conditions for the mapping operator and the input parameters (Wood et al, 1992; Dong and Shah, 1987).

Though, the method of α-level optimization requires no such conditions (Möller et al, 2000). This approach is based on a combination of evolutionary strategies, the gradient method and Monte Carlo simulations, hence high computational efforts are necessary in return. A further approach is the "transformation method" in a general or reduced form (Hanss, 2003). While the general transformation method is generally valid, the reduced transformation method may require monotony of the mapping operator. Based on the L-R representation, computational efforts are significantly minimized in the reduced transformation method by a reduction of calculations that are performed at the interval boundaries of α-cuts. The α-level optimization (Möller et al, 2000) and especially the transformation method (Hanss, 2003) appear to be suitable for an implementation of the extension principle using α-cuts. Based on these technologies, a methodology for fuzzy requests is developed and the decision-making support in the design process via compromise solution detection is rendered possible.

3.3 Concept of fuzzy requests in early design phases

The developed concept is based on the application of temporary fuzzy sets (see figure 3). Regarding the structural design, the fuzzy request sets are determined by the possibility substitution model. For this purpose, an incremental assessment of the possibility values is performed over the requested modification domain. Through expression of fuzzy requests with an assessed suitability for important modification values, the applied formalization can be used analogously by the other planning disciplines. Consequently, comparability of the request sets from the different planners is ensured and thus joint evaluations are enabled.

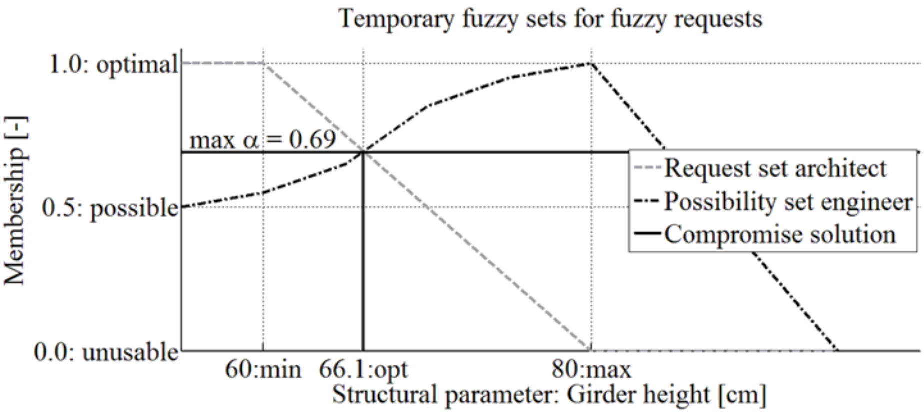

Figure 3: Detection of compromise solutions with temporary fuzzy sets

In consideration of the temporary fuzzy request sets from all design participants, the detection of compromise solutions is realizable. For this purpose, the best rated match is subsequently identified through a search algorithm that is based on the α-cut principles to find the highest possible α-value that is simultaneously valid for all included fuzzy sets. Through this α-level optimization, the most suitable modification value is determined that features the highest membership value for all involved planning disciplines. The resulting methodology of temporary fuzzy sets finally enables the integration of fuzzy requests in the design process. Thus, a computer-aided decision-making support for common multidisciplinary design changes during the process is established.

4. Substitution model extension for evaluation of design modifications

Next to the typical design changes with fuzzy requests, the current design process is characterized by further modification demands that occur after compromise detections and design selections. Such model modifications commonly result in a disproportionately high effort for the determination of remodeling needs and the redesign of the building model. Especially, the necessity to remodel limited sections or the entire load bearing system significantly influences time and costs, as the evaluation of modification impacts on the structural design involves a high complexity. Thus, the assessment of the consequences resulting from such model changes is particularly relevant for the optimization of the design process. For the determination of design modification effects, an applicable methodology is developed that is based on the engineering expert knowledge and intelligent substitution models for structural design in early phases (Steiner and Schnellenbach-Held, 2018).

4.1 Approach for the evaluation of design modifications in early phases

For this purpose, the development of fuzzy inference systems is an appropriate approach that is based on preceding knowledge analyses combined with a threshold for decision imitation. Thus, the developed methodology is premised on exploration and further application of the existing fuzzy knowledge bases. Using complementary rules that are derived from the engineering expert knowledge for parameter modifications, the processing of design changes is enabled. By extension of the mapping rules included in the substitution models, an advanced inference system is developed (see table 2 compared to table 1). The formalization of the resulting systems allows the consideration of completed structural designs as well as parameter modifications. It incorporates previous design parameters as well as the model change request for the estimation of modification effects on the applicability and design of structural elements.

The actualized possibility value of ALoD 2b that is evaluated considering the change, indicates the usability of the present structure for the modified design. Following the definition of the structural possibility, the applicability assessment is based on the interpretation of evaluated possibility values after the change. If the value exceeds a certain threshold that is inspired by the 0,5 for "possible" in the substitution model "possibility", the structure can be considered as still possible and thus a remodeling of the design is not required. In this case, the necessary adjustments of the design parameters in ALoD 3 are determined for the structural element. Otherwise, if the value falls below the threshold, the structural element must be rated as not realizable anymore and thus a model actualization in ALoD 1 and ALoD 2a is necessary or the modification has to be rejected. Thus, the assessment of model change impacts is realized through the advanced inference systems. By application of the existing knowledge bases, aspects regarding the construction, safety and economy of structural elements are integrated in the change management process. The resulting extended substitution models involve the structural engineering expert knowledge that allows the support of highly complex decision-making processes through evaluation of design modifications.

Table 2: Exemplary extended rule for modification assessment

Rule		**Parameter**		**Fuzzy set**	**Crisp value**	**ALoD**
IF		Position	=		Single-span slab	ALoD 2a
	AND	Useful load	=	“small”	2,00 kN/m²	ALoD 2a
	AND	Height	=	“small”	0,20 m	ALoD 2a
	AND	Length	=	“small”	3,00 m	ALoD 2a
	AND	Concrete class	=		C20	ALoD 3
	AND	Reinforcement	=	“small”	6,79 kg/m	ALoD 3
	AND	Height change	=	“increase”	+ 0,10 m (modification)	ALoD 2a
THEN		Possibility	=	“less”	0,5 – (– 0,5 –)	ALoD 2b
	AND	Concrete class	=		C20 still realizable	ALoD 3
	AND	Reinforcement	=	“more”	8,82 kg/m (+ 2,03 kg/m)	ALoD 3
	AND	Dead load	=	“more”	7,5 kN/m² (+ 2,5 kN/m²)	ALoD 2a

4.2 Substitution model extension

Generation of these inference systems is based on analyses of the applied engineering experience and knowledge bases that are used in the substitution models for structural design. For this purpose, the influence of parameter modifications on the structural key values is determined through sensitivity analyses. These utilize the inference systems for structural design and the included rule-based functional mapping, so that the necessary structural adjustments of the model can be determined that are reasoned by design changes. The modification impact on a structural element is evaluated through the resulting variations of the possibility in ALoD 2b and design values in ALoD 3. In addition to that, actualizations of the load transfer are considered that correspond to ALoD 2a. Thus, change impacts can be propagated to connected structural elements and consequently through the entire load bearing system. The progressions of the key parameters that are determined through the sensitivity analyses, reveal the superordinate knowledge that is applicable for the assessment of design modifications. Consequently, the resulting change management approach is based on engineering expert knowledge that includes safety, practical and economic aspects. Thus, structural engineering experience allows the support of the highly complex decision-making for the evaluation of modifications resulting in an optimization of the building design process.

4.3 Integration of learning abilities

The threshold value indicates the border point between the acceptance or rejection of a design modification. Thus, it is a key component for the imitation of underlying decision-making processes. In practice, this limit value is strongly affected by further structural engineering knowledge that is achieved through tendencies within the expert experience. Such trends can be used to further optimize the inference system for design modifications. For this purpose, the decision limit is formalized as adaptive self-learning threshold value that enables a successive inclusion of the tendencies from engineering expertise through actualizations of the limit. These adjustments are performed once the decision for the design modification is taken by the involved planners supported by the extended substitution models.

In the process, the threshold is increased, if a modification request is rejected. For the higher limit value, future modifications of the same type must produce a better suitability and thus are less likely to be recommended. Otherwise, the threshold is decreased, if a modification request is accepted. With the lower limit value, the prospective recommendation of similar design changes is more probable, as a lower possibility value is needed. Based on the training of artificial neural networks, adaptation of the threshold is performed in a softened incremental manner. This leads to a harmonization of the learning process, as strong oscillations between different choices are avoided. In doing so, the tendencies resulting from taken decisions about acceptance or rejection of design modifications are considered in the change management. Thus, the actualization of the adaptive threshold results in a successive integration of further expert experience in the decision support and an according optimization of the process.

5. Conclusions

In early phases of the building design process, an interdisciplinary planning is of high importance for the creation and modification of a building model. For an integration of the structural design perspective in the preliminary design stage, intelligent substitution models are developed. These systems are based on the application of structural engineering expert knowledge and provide a decision support for the building design development. Based on the involved knowledge formalization in fuzzy knowledge bases, methodologies for a model change management are developed that enable the consideration of the characteristic design modification requests.

During the design process, typical and common model changes often provoke conflict situations between the involved planning disciplines and lead to improper results. Using a formalization with fuzzy ranges considering the expert assessment, these modification demands are expressed as fuzzy requests enabling a compromise finding. The methodology of temporary fuzzy sets allows the integration of fuzzy requests in the early design process providing a decision support for common multidisciplinary design changes.

After the regular design process, further demands for design changes involve the modification of a completed building model, commonly resulting in disproportionately high efforts for change impact evaluation and remodeling. Based on analyses of the fuzzy knowledge bases for structural preliminary design, the inference systems of the substitution models are extended to enable an assessment of design modification effects. The resulting approach uses the engineering expert knowledge for structural design to provide a decision support for the highly complex task of processing building model modifications.

The presented change management concepts for structural design in early planning phases allow an optimization of the building design process. Therefore, continuity and integrity of the process are enhanced through decision support abilities for design modification requests. Based on the application of fuzzy methods with expert knowledge for structural engineering, the methodologies feature a high transparency and opportunities for interdisciplinary cooperation. Thus, an integration of the structural design perspective and an interdisciplinary planning are enabled to enhance the model modification processing in early design phases.

In future work, the applicability, practicability and optimization potential of the developed change management concepts are evaluated. For this purpose, practice-based and random examples for modifications of sample projects are processed by a prototypical implementation. Further development of the change management involves suggestions of model adjustments in ALoD 1 and ALoD 2a, if no usable compromise solution is detectable or the design needs to be remodeled. Following the development of the substitution model “grid”, applicable modifications of geometrical model parameters can be determined through optimization tasks.

To allow an interdisciplinary assessment, these model change recommendations from the structural design perspective can be provided as options.

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