Structural Design in early Planning Phases using Engineering Expert Knowledge and Intelligent Substitution Models

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Abstract

An early integration of the highly complex decision-making processes for structural design requires the implementation of applicable engineering expertise. For this purpose, intelligent substitution models for the structural preliminary design are developed. These are based on development level dependent structural expert knowledge. The formulation of the included engineering knowledge with Fuzzy Logic methods allows the use of linguistic variables and understandable expert rules. For the development of associated inference systems and the resulting substitution models, the basic knowledge bases are generated through parameter studies. Complementary mapping processes are supplemented by continuing optimization tasks. Considering the typical design progression of the structural preliminary design, a specialized level system is developed and related information requirements are analyzed. The substitution models contain the knowledge related inference systems and include extensive applicable engineering knowledge. Formalization of the involved engineering expertise is realized through functional fuzzy models that contain fuzzy parameters and rule-based inference systems. The resulting substitution models emulate the engineering decisions for assessments and suggestions of applicable structures. The resulting system enables the realization of a decision-making assistance for structural design in early stages and for modification processes. As a result, designers are provided with an early support of complex design decisions allowing high efficiency gains. Included are the recommendations for feasible and economically optimized designs as well as their preliminary dimensioning. Consequently, the intelligent substitution models include the necessary level dependent engineering expertise. Thus, an appropriate decision support is integrated into the design process. The resulting consideration of the structural planning perspective in early phases enables a successful design of buildings and an improved planning progression. Finally, the provided support of the design in early planning phases enables a harmonization and an efficiency enhancement of the design process. For demonstration of the enhanced planning process, the design of a fictional building model is performed with illustration of the decision-making assistance by the developed substitution models. Two common design progressions are presented that are based on different planning perspectives. For the structural engineering point of view, the typical process is executed according to the developed level system. Another advanced architectural perspective entails an alternative development level system. The application of the substitution models for different approaches is enabled through adaptive detailing concepts that allow assignments of the structural design levels to alternating systems.

Keywords: Formalization of engineering knowledge, decision support using expert knowledge, fuzzy inference systems, preliminary structural design, building design scenarios.

1. Introduction

In early phases of the building planning process, the structural concept significantly influences the quality of a design (Zhang et al, 2018) and the factors time and costs of an architecture (Kim et al, 2015). As creative and functional aspects are the essential basis for the common design procedure, only few and rough planning principles are allowed for structural evaluations. Thus, assurance of applicability and efficiency of a building design requires the early integration of the structural engineering perspective in the planning process and the following collaboration of all involved planners (Schnellenbach-Held and Hartmann, 2003; Oh et al, 2015; El-Diraby et al, 2017). In the resulting interdisciplinary design process, simplified formulae and especially the engineering experience of the structural engineers are usable for design assessments that are based on few and rough boundary conditions in early phases (Schnellenbach-Held and Albert, 2003). The appropriate engineering expert knowledge is related to different development levels (Maier et al, 2017) and necessitates an applicable formalization approach (Steiner, 2018) as well as extensive structural analyses and simulations (Liu et al, 2018). Using the resulting knowledge and related evaluation tools, the complex task of structural decision-making support and an associated interdisciplinarity are enabled in early planning phases (Schnellenbach-Held et al, 2006). For this purpose, intelligent substitution models are developed that are based on development-level dependent fuzzy knowledge bases for structural preliminary design (Schnellenbach-Held and Steiner, 2018). Exemplary progressions of the enhanced planning process are demonstrated with the aid of illustrative building design scenarios.

2. Structural design in early planning phases

The integration of the structural engineering perspective in early phases of the building planning process is realized through intelligent substitution models for the structural preliminary design (pre-design). For this purpose, representative adaptive levels of development (ALoD) are identified for the structural assessments of building models. Applicable engineering expert knowledge for the different design states is formalized using methods of Fuzzy Logic. Parameter studies and optimization tasks are performed to generate structural information for fuzzy knowledge bases to include the engineering experience. The simulation of associated decision-making processes is realized through inference systems that form the basis for the intelligent substitution models. The resulting systems enable the decision support for structural pre-design through the integration of the structural engineering perspective in early planning phases of building design. Thus, an optimization of the design process is facilitated through harmonization effects and efficiency increases (Steiner and Schnellenbach-Held, 2018).

2.1 Adaptive levels of development for structural pre-design

For the consideration of the structural design requirements, a specialized detailing system (see figure 1) is developed that contains five adaptive levels of development (ALoDs). According to the common design process from structural engineering perspective, the basic understanding and related parameters for load bearing systems are included. Additionally, transfer functions are introduced for the determination of complementary building model information that are realized as the intelligent substitution models. They evaluate the required parameters for the following design status based on the limited data of the lower ALoD. The building model development according to the ALoD system is demonstrated in the structural design scenario. As starting point for the design progression, the “ALoD 0” is defined as blackbox that contains global information as well as environmental and boundary conditions. The following architectural development of a room plan leads to the “ALoD 1” that involves the geometrical parameters of the building components and is comparable to the physical building model. Based on the subsequent positioning, the typical idealization of the load bearing elements is introduced in the “ALoD 2a” that resembles an analytical model. The common positions represent the basis for the evaluation and the design of structures that is realized through engineering expert knowledge according to conventional calculation approaches. As alternative to the architectural specifications, the substitution model “grid” performs an estimation for the arrangement of optimized components based on analyzed structural design knowledge. The suitability of different construction types for the structural positions is content of the “ALoD 2b” and determined by the substitution model “possibility”. Thus, the engineering experience based expert assessment is simulated, allowing a support of the decision-making process for the preliminary design and the change management of building models. For the selected construction, the characteristic structural parameters are determined through the substitution model “pre-design”. By complementation of the conclusive specifications that are content to the final “ALoD 3“, the preliminary design of the structural elements is finished and further analyses of the building model are allowed (Steiner and Schnellenbach-Held, 2018).

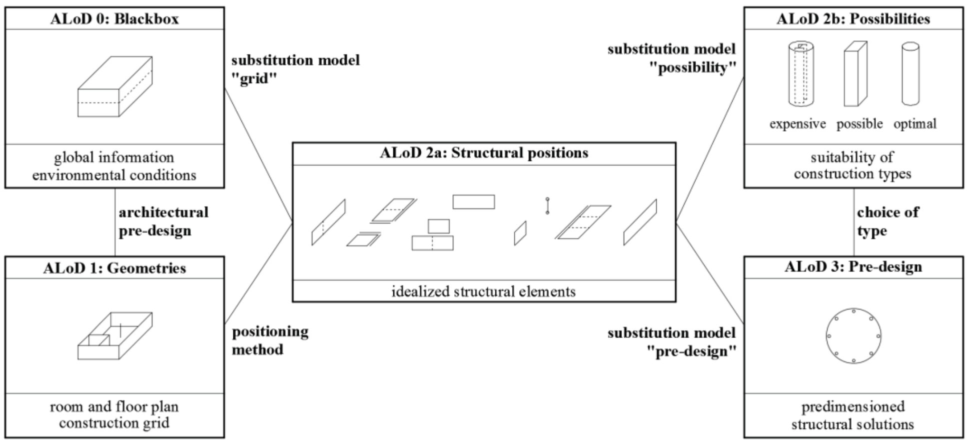


Figure 1: Development levels for structural design based on Steiner and Schnellenbach-Held 2018

2.2 Intelligent substitution models for structural pre-design

The developed intelligent substitution models for structural assessments and preliminary design are based on the application of associated engineering experience. This expertise is expressed using Fuzzy Logic methods, so that the utilization of expert knowledge and rule-based inference systems is allowed. Using such systems, the human decision-making mechanisms and reasoning competences are imitable even under most complex conditions, as extraordinary generalization abilities are featured (Steiner and Schnellenbach-Held, 2017). Following the formalization approach, ALoD-dependent fuzzy knowledge bases are developed for the inclusion of applicable engineering expert knowledge. The included assessment and design of load bearing elements is based on binding codes and directive standards as well as the knowledge, experience and competence in the field of structural engineering. Being phrased in the Modus Ponens “if premise (lower ALoD), then conclusion (higher ALoD)”, the resulting rule bases are transparent and easy to understand (see table 1). The related decision-making processes that enable the knowledge-based evaluation of model parameters for the design development, are realized as functional TSK fuzzy inference systems (Steiner and Schnellenbach-Held, 2018).

For the typical idealized structural elements (ALoD 2a), parameter studies are performed at the related calculation models to generate the expert knowledge. Adequate value boundaries and parameter samplings of the studies are determined through common engineering experience. The determination of the usability (ALoD 2b) and the design values (ALoD 3) of the elements is based on the satisfaction of the required limit states according to Eurocode. If all design criteria are satisfied, the plannable structure is qualified as “possible”. Otherwise, the assessment of infringing elements is formulated as “not realizable”. A further refinement of the possibility is based on additional expert knowledge for structural assessments. To meet the large number of possible structures for certain boundary conditions, the search for a minimized approximate realization effort is performed by optimization tasks. For the optima, the expression as expert rules is practicable and allows a verification with common engineering experience. Subsequently, a comparison basis for design choices and change management is established through update of the expert assessment (ALoD 2b) with the complementary knowledge. The estimation of construction grids featuring applicable and optimized structural elements (ALoD 2a) is based on superordinate rules that are identified through analyses of the resulting engineering assessment knowledge. Finally, the rule bases are derived from the incrementally approximated functions for structural design forming the inference systems of the resulting substitution models. For the building design process, they allow a reliable decision support that enables the integration of the structural engineering perspective in early phases (Steiner, 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*

3. Scenarios for exemplary enhanced design processes

The support of the building design process is demonstrated with the aid of illustrative exemplary simple scenarios. For this purpose, the design of a fictional building model is performed with illustration of the decision-making assistance by the developed substitution models. Two common design progressions are represented that are based on different planning perspectives. For structural engineering, the typical process is executed according to the developed ALoD-system (Schnellenbach-Held and Steiner, 2018). Another point of view results from an advanced architectural perspective that entails an alternative development level system (Abualdenien and Borrmann, 2019). The application of the substitution models for the different BDL approach is enabled through adaptivity of the ALoD concept that allows an assignment of the structural design levels to alternating systems. Additionally, the realized decision support includes the integration of suggested options (Mattern and König, 2018) to improve the support acceptance and to allow further comparative analyses like energy efficiency calculations (Geyer et al, 2018; Harter et al, 2018). For involved communication aspects (Zahedi and Petzold, 2018), the data flow of the model parameters for structural design purposes is outlined. The resulting demonstrations show the enhancement of multidisciplinary building design assessments through engineering expert knowledge and the developed intelligent substitution models.

3.1 Basic structural design scenario

The scenario starts with the specification of a blackbox in ALoD 0 that is represented by the external total lengths and height as well as the shape of the building. Additional data is requested regarding the global information and environmental conditions. The significant parameters are the usage category for the useful load estimation, the soil condition for foundation assessments and the global location for further influences like earthquakes and exposures like see salt. In this stage, different dimensions and building shapes might be considered as options that are specified by participants like the architect or the building owner. Based on the blackbox, two procedures are feasible for the determination of the building elements. In the common design process, the architect provides a floor plan with complete geometrical specifications. Apart from that, a construction grid can be estimated based on structural engineering knowledge through the substitution model “grid”. Either way, the inserted typical idealized elements allow the application of common engineering expert knowledge for the assessment and preliminary design of load bearing structures. For this further processing, required parameters of single positions in ALoD 2a are the element type, boundary conditions, the lengths, the height and the load. Based on the given specifications in ALoD 0, the useful load is derived from the usage category and the foundation of the footings is evaluated from the soil condition. The continuing load transfer of the bearing structure is premised on a specified path that follows from slabs to vertical elements and from top to bottom. If the floor plan is provided by the architect, the development level of the model is raised from ALoD 0 to ALoD 1. Essential included parameters are the number and heights of floors, the arrangement of vertical building elements, slab and wall thicknesses, column cross-sections and openings. Thereby, considerable options are different floor and room compilations that might be suggested and mainly differ in the partial heights and lengths of the model or in the building construction type regarding wall and column arrangements. With the included geometrical information, the structural positions are identifiable through the positioning method raising the development level from ALoD 1 to ALoD 2a.

Otherwise, an estimation of the construction grid is realizable by using appropriate structural engineering knowledge that is essential content of the substitution model “grid”. The performed determination of a grid system and the related arrangement of vertical elements increases the model development status from ALoD 0 to ALoD 2a. For this purpose, suggestions for the specification of floors and slab kinds are necessary to enable the knowledge driven detection of structurally optimized segmentations of the total height and lengths. The buckling length of compression members highly influences the design of the vertical elements. Thus, floor configurations are proposed that are based on the division of the total height by common floor heights. Thereby, options are integrated for many small and few tall floors (see figure 2). Through the kind of slab, more specifically through the support types, suitable partial lengths are determined that are based on maximal slab position lengths featuring high possibility values for common slab thicknesses in consideration of the useful load. In the process, the resulting slab positions as well as the placement of wall and column positions for continuous and point supports are identified. For the consequential horizontal partitioning, further options are introduced for different slab bearing kinds and slab thicknesses (see figure 3). The resulting recommendation of construction grid systems involves the combination of options for floors and slab types (see figure 4). Analogously to the optimal slab position lengths and with respect to the load transfer, similar structural knowledge is utilized for the determination of wall thicknesses, column cross sections and footing dimensions to complement the building model for ALoD 2a. Thereby, different material or profile types are considerable through integration of options for various element styles.

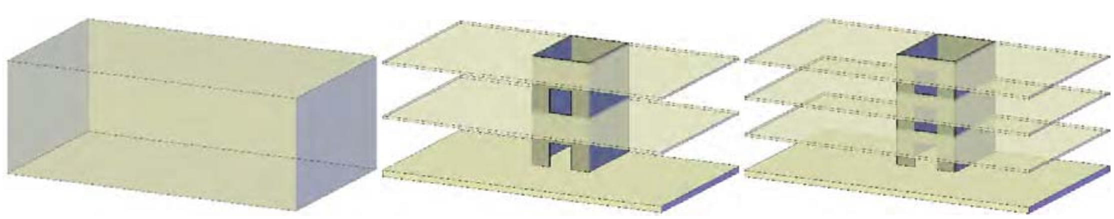


Figure 2: Blackbox in ALoD 0 and exemplary floor suggestions with anticipated stiffening core

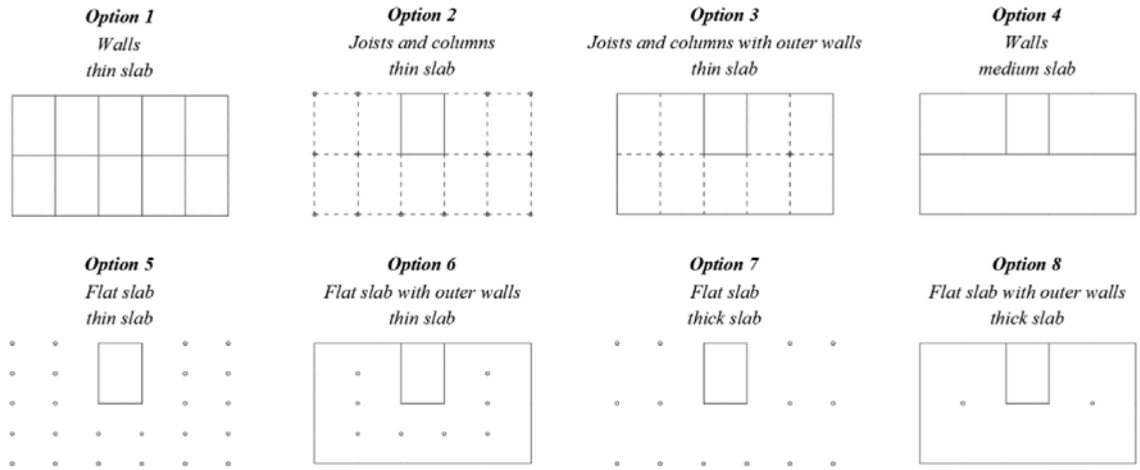
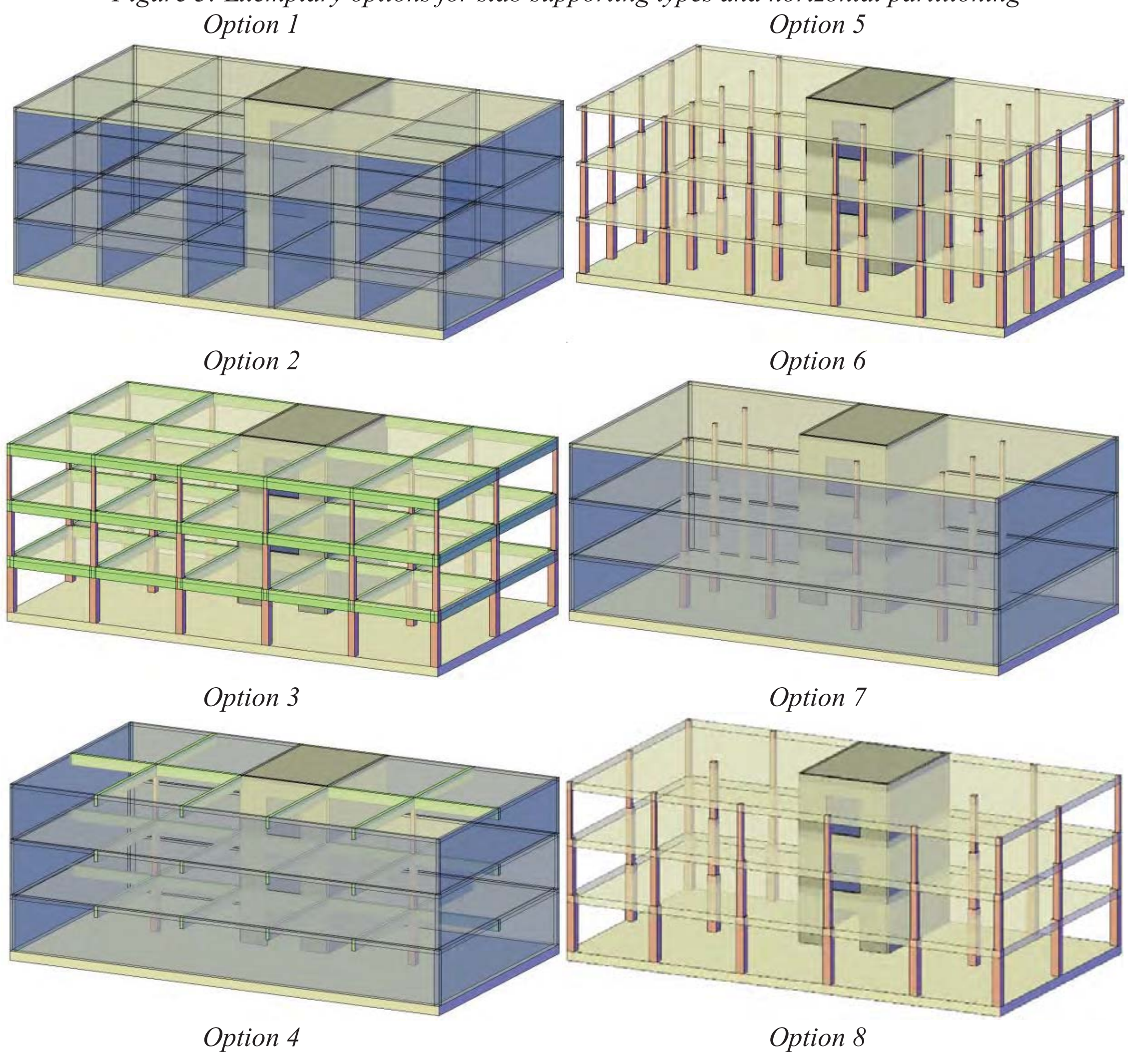


Figure 3: Exemplary options for slab supporting types and horizontal partitioning



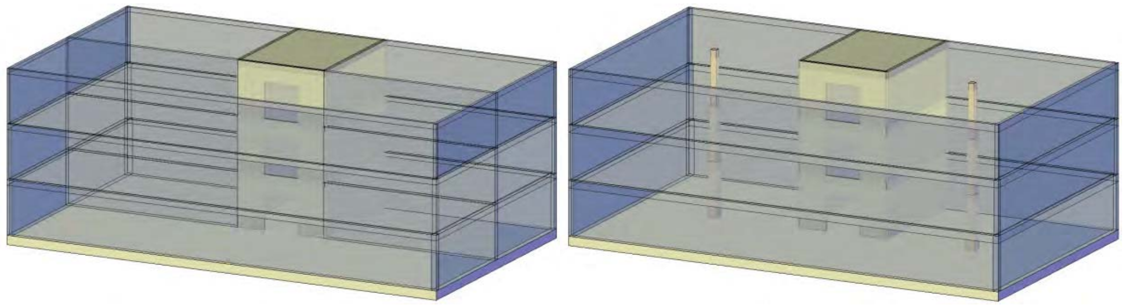


Figure 4: Exemplary models in ALoD 2a following the suggested grid options with three floors

The resulting structural element related information in ALoD 2a allows the possibility assessment through the substitution model "possibility" that raises the development level of the model to ALoD 2b. For each position in each option, the evaluated possibility values indicate the structural rating that is based on engineering expert knowledge for different construction types. Calculations of the values are based on the specific structural component and its parameters for geometry and load in ALoD 2a. If the construction grid is suggested through the substitution model "grid", high possibility values are expected, as these indicate highly applicable elements. The delivery of a floor plan by the architect might trigger fuzzy requests, as low structural ratings are expectable more easily due to the different design perspective. This change management concept is performed for model modification requests in ALoD 2a and is based on assessments through the possibility values in ALoD 2b (Steiner and Schnellenbach-Held, 2018; Schnellenbach-Held and Steiner, 2019). With the structural evaluation of the building model, the selection of an appropriate option regarding the possible construction types is encouraged and the relating design decisions are supported.

For the selected designs, the final parameters for the preliminary design are determined by the substitution model "pre-design" that raises the development level from ALoD 2b to ALoD 3. The performed assessment of the exact material, the reinforcement and potential complementary information in ALoD 3 is based on the generated engineering expert knowledge. For the consideration of supplementary parameters, the ALoD-system features according concepts of adaptive detailing, so that further structures like precasted elements, assembly parts or other construction types are specifiable. With the geometry and load of the elements in ALoD 2a, the estimations are executed for the specific structural positions featuring the highest possibility values in ALoD 2b. In the process, options are considerable for different material strengths leading to varying reinforcement masses. By integration of the final model parameters, the building model assessment for the preliminary design is finished from the structural engineering perspective.

3.2 Alternating design progression

Through adaptivity of the developed ALoD system, the utilization of the same engineering expert knowledge and substitution models for structural assessments is enabled for alternating detailing approaches and related design progressions (Steiner and Schnellenbach-Held, 2018). For this purpose, the simultaneous presence of structural elements in different ALoDs as well as a related substitution model splitting are allowed. In the process, the consideration of partial parameter pre-specifications and of the varying information flow is needed. The application of the developed detailing and assessment system for structural engineering on an alternating design procedure is demonstrated by means of a meta model approach that includes another development level specification with building design levels (BDLs) (Abualdenien and Borrmann, 2019). The principle of adaptive detailing is outlined per ALoD to BDL adjustments (see table 2) and according separations of the inference systems. Due to the adaptation induced increase of the development resolution that especially arises from segmentations of the substitution model "grid", more exemplary starting points for fuzzy requests are presentable. Through the adaptivity of the developed ALoD concept, the structural engineering perspective is integrated in alternating design progressions, allowing an improvement of interdisciplinary design procedures in early planning phases.

Table 2: Assignment of ALoDs to the BDL system

BDL	***Basic representation***	***ALoD***	***Allocated information***
1	*Building footprint on site surface*	*0*	*Shape and total lengths*
2	*Exterior surfaces*	*0*	*Total height*
3	*Exterior solids* *Slab thicknesses adapted from BDL 4* *Interior centerlines*	*1* *2a* *Partial 2b* *1* *Partial 2a*	*Geometry exterior elements* *Exterior elements* *Material type exterior elements* *Suggested slab thicknesses* *Interior elements without geometry*
4	*Exterior openings* *Interior solids*	*1* *1* *2a* *Partial 2b*	*Exterior openings* *Geometry interior elements* *Interior elements* *Material type interior elements*
5	*Interior openings* *Added structural design parameters* *Exterior layering*	*1* *3* *-*	*Interior openings* *Structural design parameters*

Based on an architectural perspective primary in the context of energy calculation demands, the BDL concept is a development level basis for an interdisciplinary building design process (Abualdenien et al, 2019). For the building model development in early stages, the BDL system provides five basic design levels (Abualdenien and Borrmann, 2019) that depend on geometrical specifications separated for exterior and interior components. The building footprint on the site surface in BDL 1 and the exterior building surfaces in BDL 2 are assignable to the blackbox in ALoD 0 including the global and environmental parameters. As before, the construction grid can be provided by other planning participants or estimated through structural engineering knowledge.

In contrast to the structural design process, the following BDL 3 (see figure 5) contains surfaces and centerlines for interior elements (partial ALoD 2a) in combination with solids (ALoD 2a) and material groups (partial ALoD 2b) for exterior components. Next to the specification by the architect followed by the positioning method, the principle layout of the slab positions and the according arrangement of vertical elements are determinable through the parts of the substitution model "grid" that are relevant for slab divisions. In consideration of the slab thickness suggested for BDL 4 (ALoD 1), the estimated slab partial lengths (ALoD 2a) are used to introduce approximate centerlines of vertical elements (partial ALoD 2a). This enables the determination of the load transfer that is necessary for the design evaluation of vertical structural elements. Subsequently, the layout of exterior components (ALoD 1, 2a) that especially are the roof slab and exterior walls, is determined through the related parts of the substitution model "grid". Suitable material groups for the exterior elements are evaluated based on the possibility values (partial ALoD 2b) calculated by the substitution model "possibility" for the associated construction types. In the grid suggestion process, options are introducible for slab support types and slab heights as well as the layout and material groups – like masonry or aerated concrete for walls – of the exterior elements. The placement of a column is an example for potential fuzzy requests in the resulting BDL 3.

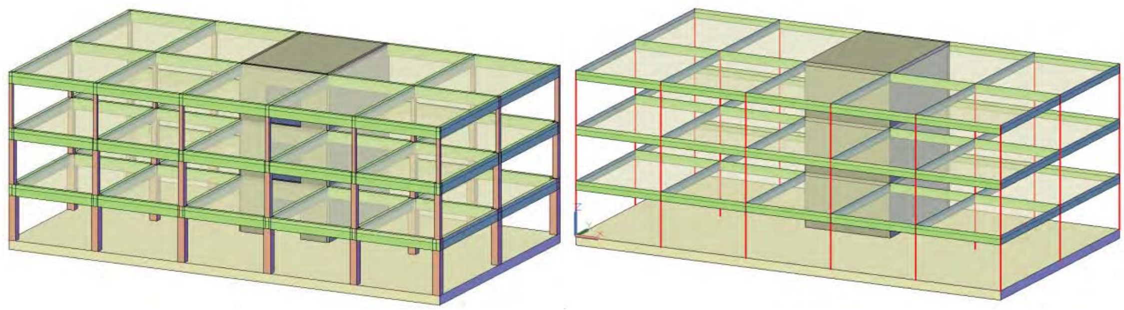


Figure 5: Comparison of ALoD 2a (left) and BDL 3 (right)

In BDL 4, parameters for exterior openings (ALoD 1) as well as solids (ALoD 1, 2a) and material groups (partial ALoD 2b) for interior structures are added to the building model. As openings to the outside that are inserted especially for doors and windows, may influence the wall layout, the possibility value might be reevaluated for exterior structures, if an earlier specification is missing. Analogously to the exterior components, the layout of interior elements is determined through the related parts of the substitution model "grid" combined with the possibility values for different construction types that are depending on material groups and calculated by the substitution model "possibility". In the process, options are presentable for the layout and material groups of the interior elements. Possible fuzzy requests in BDL 4 are, for instance, the adjustment of a beam height or the change of a column cross section. The final BDL 5 contains interior openings (ALoD 1), the layering of exterior components and ventilation information as well as the complemented structural design parameters (ALoD 3). Included are the exact material class, the reinforcement amount and possible construction related information. Like in the basic scenario, adaptive detailing concepts allow the consideration of further construction types. The determination of the structural information is realized by the substitution model "pre-design" for the exterior and the interior elements. Thereby, options are providable for different material strengths and fuzzy requests can exemplarily address the modification of openings in beams. By supplementation of the final parameters, the building model is developed to BDL 5 and the structural engineering assessment of the preliminary design is finished.

4. Conclusions

Interdisciplinarity is a significant factor for a successful planning in the building design process. Additionally, the supporting structure highly influences the applicability and efficiency of a building design. For these reasons, an integration of the structural engineering perspective in early planning phases is realized through the developed intelligent substitution models for preliminary structural assessments and design. They provide a decision support for the building design process based on structural engineering expert knowledge. For this purpose, fuzzy knowledge bases are formalized and generated that depend on identified development levels for structural design. Using a Fuzzy Logic approach, inference systems are developed for the expert knowledge to form the intelligent substitution models. Applicable structural engineering knowledge is generated through parameter studies and optimization tasks as well as complementary mapping processes. For demonstration of the enhanced building design process, two design scenarios for a simple fictional building are illustrated that involve the decision-making assistance. According to the developed ALoD-system, the first scenario follows the common progression for structural design. A different design procedure is based on an advanced architectural perspective that reveals an alternative development level system. Through adaptive detailing concepts that are integrated in the ALoD-system, the application of the developed intelligent substitution models is allowed for the differing design process.

Based on the evaluated design parameters, further model ratings from other planning disciplines are allowed. These may involve financial calculations or embedded and operational energy estimations for life cycle energy analyses (Abualdenien et al, 2019). As the integrated options represent an uncertainty of parameters in lower development levels, related quantification methods are enabled. For example, value ranges for grey energy or financial demands are determinable through backpropagation of option induced structural parameter variations. Additionally, requests for modification of the completed model take place that are characteristic for the current design process. As such changes usually provoke high efforts for impact evaluations and remodeling, a suitable change management is enabled by a methodology for structural assessments. The concept is based on the extension of the applied substitution models and the included engineering expert knowledge (Steiner and Schnellenbach-Held, 2018; Schnellenbach-Held and Steiner, 2019). The resulting decision support allows an optimization of the design process through enhancements of the continuity and the integrity.

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