Topological Queries and Analysis of School Buildings Based on Building Information Modeling (BIM) Using Parametric Design Tools and Visual Programming to Develop New Building Typologies

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School buildings are currently one of the largest portions of planning and building projects in Germany. In order to reflect the continuous developments in school building construction with constantly changing spatial requirements, an approach to analyse, derive and combine patterns of schools is proposed to adapt school typologies accordingly. Therefore, the topology is analysed, concerning interconnection methods, such as adjacency, accessibility, depth, and flow. The geometric analysis of e.g. room sizes or spatial proportions is enhanced by including grouping of rooms, estimated room clusters, or room shapes. Furthermore, text-matching is used to determine e.g. room program fulfilment, or assigning functional room descriptions to predefined room types, revealing huge differences of terms throughout time and architects. First results of the analyses show a relevant correlation between spatial proportion and room types.

Keywords: *school building typologies, building information modeling (BIM), artificial intelligence (AI), topology, spatial analysis, digital semantic model*

INTRODUCTION

The development of architecture is characterised by continuous change due to social, ecological and technological conditions. Contemporary and future building tasks take place against the background of the change of these framework conditions. The change in formal language of architecture, because of industrialisation and composite building material, resulted in classical modernism, with representatives like Le Corbusier or the Bauhaus, as the starting point of the design methodology movement (Richter 2010).

The ideas of classical modernism in architecture and novel scientific and computer-aided methods led to the first generation of the design methodology movement in the 1950s and 1960s, e.g. represented by Christopher Alexander or Niklas Luhmann. In the 1970s the second generation of the design methodology movement, represented by Horst Rittel and others, did not view design procedurally as the fulfilment of requirements, but rather as an individual process that could only be described incompletely (Richter 2010). In the 1980s, the digital approaches of case-based reasoning (CBR) influenced the digital building design approaches, which led to the rise of a field of AI research in the building industry, called case-based design (CBD), in the 1990s. Even though at a current perspective the systemisation of complex cases in architecture is not sufficiently solved and is referred to as data acquisition bottleneck. For the formalisation of building information, object-oriented approaches (Eastman 1999) of product data modelling have been transferred to the construction industry in the 1990s. To remedy these shortcomings, Langenhan (2010, 2013, 2017) introduced the approach of "semantic building fingerprints" that facilitates spatial relationships and their digital processing based on enriched digital semantic building data. The digital semantic fingerprint of buildings was introduced to describe the main features of the design, forming the basis for similarity assessment to deal with ambiguities and complexities of architecture.

After major school building construction activities at the beginning of the 20th century and in the 1970s, Germany is now experiencing a third wave of school construction (Wenzel 2019). The renovation backlog of existing buildings and the current population growth requires school expansions and new buildings for all age groups and levels of education. The influx into conurbations is aggravating the situation regionally. In addition to the number of pupils and the necessary capacities, other use-specific changes demand structural quality and flexibility of contemporary school buildings, e.g. for all-day schools, for which the buildings designed as half-day schools are insufficiently designed. Moreover, new pedagogical concepts for integration, inclusion and digitalisation require new floor plan typologies, while considering old or constant requirements, such as large simultaneous circulation of people. While these old and new requirements are partly contradictory, schools are currently being designed in elaborate planning processes to develop new functioning building typologies. Therefore, new functioning building typologies have to be developed, while understanding and classifying existing facilities.

PROBLEM STATEMENT

The amount of school building constructions, renovations, and expansions has constantly increased (Freireiss and Commerell 2019). Throughout history, schools, being the educational space, are a mirror of the economical essence and ideal of the current economy (Schmidt and Schuster 2014) by shaping the child into the most suitable citizen for the country's current society (Opp and Bauer, 2010). Increasing globalisation results in an international competition for high quality education and intellectuals as national assets (Freireiss and Commerell 2019). Furthermore schools, representing a point of congregation and integration, are conceptual entities for cultural, social and intellectual education, as well as physical institutions, providing space for cultivating and developing the urban context.

These educational facilities are the space, where a child is consciously perceiving social experience, responsibilities and possibilities within a society for the first time. This artificial and controlled 'Micro Society' (Schmidt and Schuster 2014) is separated from the exterior space to trial and learn, described as the 'Third space for social interaction' by Opp and Brosch (Opp and Bauer 2014). As early as the 1950s, Reisinger and Schirmer express the need for school buildings to follow the new pedagogical methods, declaring it the 'second home', (1955), verified more than 60 years later by Djahanschah, Auer, and Nagler

(2018). By exceeding the studying space and providing a suitable atmosphere for children, the school ensures the well-being through architecture psychology (Opp and Bauer 2010) and the four qualities of residency, the thermic, hygienic, visual and acoustic (Djahanschah, Auer, and Nagler 2018). In order to maximise the capabilities and progress of the child, an efficient educational infrastructure and a versatile, but appropriate, environment must be introduced. The pedagogue Gerald Hüthers bases this complex ambience on a multifaceted experience, and the confrontation of the familiar and the unknown, stimulating the mental and intellectual growth (Schmidt and Schuster 2014). Opp and Bauer (2010), and Freireiss and Commerell (2019) go even further to declare the 'Room' itself as the entity of the 'Third teacher' by utilising the familiar space, derived from the pedagogical concepts of Reggio. Overall, a school building is a physical institution, which serves as a framework to deliver the entity of a pedagogical concept to increase intellectual development, the social upbringing, and cultural education.

In the introduction of the 'Grundrissfibel' (eng.: Reference work for floor plans) for school buildings Hönig and Nashed state that the actual facilities often outlive pedagogical concepts. Therefore, these buildings must be much more flexible and robust than other typologies (2015). Reisinger and Schirmer strongly agree to design, plan and build schools with the future in mind (1955). Djahanschah, Auer, and Nagler use the concept of 'Kaizen' as the basis for their designs. The Japanese concept suggests that every product or process can be improved (2018), resulting in a constant change of school buildings (Freireiss and Commerell 2019). It does not necessarily call for the demolition and replacement of old facilities, but also maintaining old, functioning buildings, which only need minor renovations because of their long-time acceptance by society and users (Djahanschah, Auer, and Nagler 2018).

Due to these various reasons, such as historical and political context, social and cultural aspects, pedagogical influences, and developments within architecture, the typologies of schools are very complex because of e.g. legal regulations and changing requirements on schools because of e.g. group teaching concepts, instead of frontal teaching by an authority figure. Schools are designed through an interdisciplinary process with careful consideration of all aspects and users of the building, like teachers, students, personel, and the public. In order to categorise and recognise patterns in a case-base, solely essential information is to be extracted from the vast amount of data, meta-information decoded and processed, and its terminology conformed. This school data will be used to generate school variations based on a semi-automatic approach steering a combined system that uses case-based reasoning and deep-learning technologies to analyse and classify facilities according to the external influence, such as history and politics. Further, it is a planning support system for schools to rapidly get new school typologies for constantly changing requirements based on best practice schools.

RELATED WORK

During the first half of 19th century the facility of a school was an open-plan room within the private home of the village teacher, called 'Einraumschule', where groups of different ages were assigned appropriate tasks (Djahanschah, Auer, and Nagler 2018) (Schmidt and Schuster 2014).

As educational institutes are a political demonstration of cultural and intellectual capabilities (Djahanschah, Auer, and Nagler 2018), in the 19th century schools and educational concepts, such as frontal teaching, were based on military methods. The 'Gangschule' (eng.: Corridor school) was built for optimising this teaching method of large classes, approximately 70 students, which aligned classrooms along one large hallway within a single-depth building (Djahanschah, Auer, and Nagler 2018) (see Figure 1). Around 1900 the teachings of Montessori were introduced, which contained an important component for social learning and assisting the child to learn for itself, still utilising an east-facing 'Gangschule' (Djahanschah, Auer, and Nagler 2018).

Figure 1
Schools in Lichtenberg, Berlin. Schmidt, M. et al., Schulgesellschaft: vom Dazwischen zum Lernraum, Future school buildings, Berlin, Jovis, 2014, p.18.

Especially after 1945, the construction of school buildings rapidly increased (Djahanschah, Auer, and Nagler 2018) and on a political level, German federalism was reintroduced, including that each of the 16 federal states has its own ministry of education. Therefore, the different German states created different school systems and thus, different school building regulations, which are further specified on a communal level. In order to distance themselves from the former pedagogic methods, authoritarian politics and the architectural form language of the 'Gangschule', pavilion schools were introduced (Djahanschah, Auer, and Nagler 2018). Newly constructed buildings, which Reisinger and Schirmer, as employees of the Ministry of Reconstruction of 1955, advocate, emphasize a lot on light, flexibility, expansion, and greenery for playing and movement, but still separate the children by age and gender (1955). They implement these attributes and spaces into the typical 'Gangschule' and finally, advise to use housing technology on a reasonable level (Reisinger and Schirmer 1955).

The schools of the 1960s and 1970s became a space for exchange, equality, information, studies and retreat as the essence of democracy (Schmidt and Schuster 2014) (Djahanschah, Auer and Nagler 2018). Due to the highest number of school enrolment after the Second World War, school buildings became much larger, often called school centres, planned in the manner of a 'Gangschule' as a double-depth building or 'Atriumschule' (eng.: Atrium school), using light-weight construction (Bayerische Fertigbau GmbH 1974). Later it became known that those buildings often led to inferior air quality and even to the 'Sick-building-syndrome', due to fixed glazing and even faulty fully ventilated buildings (Djahanschah, Auer, and Nagler 2018).

The performance of Germany in the PISA ranking in 2000 motivated a reformation of the pedagogical methods and the definite inclusion of pedagogical concepts into school building design was prompted, like Reisinger and Schirmer had already advised 65 years ago (1955). As buildings need to support these concepts, smaller bundled classrooms, separated by flexible walls are arranged around a central common room called 'Marktplatz' (eng.: Marketplace) (see Figure 2). These study clusters or 'Lernlandschaften' (eng.: Study landscapes), derived from the 'Einraumschule' (Djahanschah, Auer, and Nagler 2018), support the dynamic studying of students supporting other students, which stimulates intellectual growth and social skills (Opp and Bauer 2010). Because of these pedagogical concepts, mixed schools of different ages are preferred, as it improves the development of all the children and promotion of talents, and simplifies the transition from one grade into another (Freireiss and Commerell 2019). Further, the future of educational methods suggest team teaching, or co-teaching, of at least two teachers, as well as the student becoming the teacher (Schmidt and Schuster 2014).

Figure 2
First floor of primary school in Karlsfeld by ALN GmbH.

As largely both parents work full-time and students currently remain more hours at school, space for staying, retreat, and supervision is needed in contemporary buildings (Djahanschah, Auer, and Nagler 2018) (Kurz 2015). The circulation area is now used as additional space or vacant classrooms are repurposed during non-used times (Kurz 2015). Schmidt and Schuster call this the 'In-between space', the physical representation of the pedagogical entity of the school (2014). The contemporary facilities are shaped by limited space, especially in metropolitan areas due to rising student numbers (Freireiss and Commerell 2019) and declining space. Consequently, the area per student has increased. During the 19th century it was about 0.9 m^2, between 1945 and 2000 it increased to $2m^2$ and finally, in the 'Lernlandschaften' $4m^2$ are provided per child (Djahanschah, Auer, and Nagler 2018). Furthermore, Kurz sees the need for school buildings to open themselves up to the public and offer space as a cultural and social convergence point and for further education for adults (2015). Conveying the notion of a cultural centre amidst a district, schools can also present themselves as a public space, by incorporating service centres, public playgrounds and community centres (Schmidt and Schuster 2014). Furthermore, these buildings can be used as landmarks within areas for orientation and urban planning, due to their form language and positioning (Djahanschah, Auer and Nagler 2018). Therefore, Freireiss and Commerell call the school an 'urban component' (2019).

The experimental 'Open school' in Uto in Japan is a possible future school typology (see Figure 3). L-shaped walls define an open space of a room with nomadic classes, which are changing location for every class. It is supported by the team teaching method and the ability of the rooms to open up the facade and include the exterior as further space in summer.

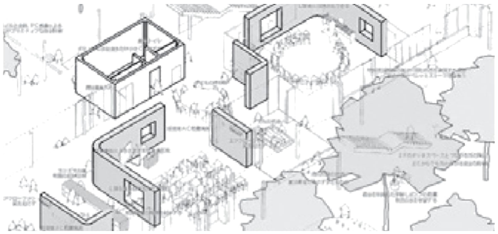


Figure 3
'Open School' in Uto, Japan. Schmidt, M. and Schuster, R., Schulgesellschaft: vom Dazwischen zum Lernraum, Future school buildings, Berlin, Jovis, 2014, p. 93.

APPROACH

Due to this high amount of factors and requirements, schools include a complex topology and high amount of room types. Even though the design focus of the contemporary twelve schools of 'Future school buildings' (Freireiss and Commerell 2019) is different, the room program is quite similar. These buildings are commonly two storeys high in the countryside, while within the metropolitan area and its resulting lack of space, they tend to be higher, rising up to a maximum of five floors. The different facilities focus on the pedagogical integration of multiple school types with classrooms, study rooms, group rooms, laboratories and space for music, art and theatrical teachings, while providing separate rooms for personnel and teachers, administration, housing technology, storage, meeting rooms, sports facilities, and a large meeting hall, called 'Aula'. A cafeteria, grouped with a kitchen and preparation area, is incorporated, as well as one or more multipurpose rooms, storage spaces, relaxation areas, playgrounds and a function room for events, such as theatrical plays or concerts as a point of congregation for social and cultural interaction through recurring events. Depending on the curriculum, the room program needs to provide specialised spaces like workshops or rooms equipped with advanced technology. The adjoining greenery, an area for playing and movement, is often used as a 'Freiluftklassenzimmer' (eng.: Outdoor classroom) within an assigned space, sometimes with experimental gardens, as well as a public space.

To transform spatial configurations of schools like topological, semantic and geometric information in a computer readable way to serve as a case-base for the generation of variations, using deep-learning, the necessary information is stored in the architectural GraphML (aGraphML) format (Langenhan 2017), derived from the fluent graph format of GraphML, based on the XML format. It is used to depict adjacency, accessibility, depth, flow and analysis of the room program to the user in Rhino3D and Grasshopper3D in a readable visualisation. The Dolphin plugin (Langenhan 2015) for Grasshopper3D, provides a component to translate into said file format. In the following, the workflow through the different software programs is described, as well as the different steps to convert the extracted information of an Industry Foundation Classes (IFC) file into an aGraphML format to analyse school buildings and generate variations as part of our future work. Furthermore, the results of the variant generation is to be used in Autodesk Revit in later stages.

This workflow offers a software overview, picturing the different programs and plugins, which are currently available, to translate an IFC file format into an aGraphML file format (see Figure 4). For this project REVIT 2020 from Autodesk was used. The plugin Rhino.Inside for REVIT 2020, developed by McNeel, is based on the Rhino3D 7 Work-In-Progress (WIP). It allows extracting and working in real-time with REVIT elements in a separate Rhino window,

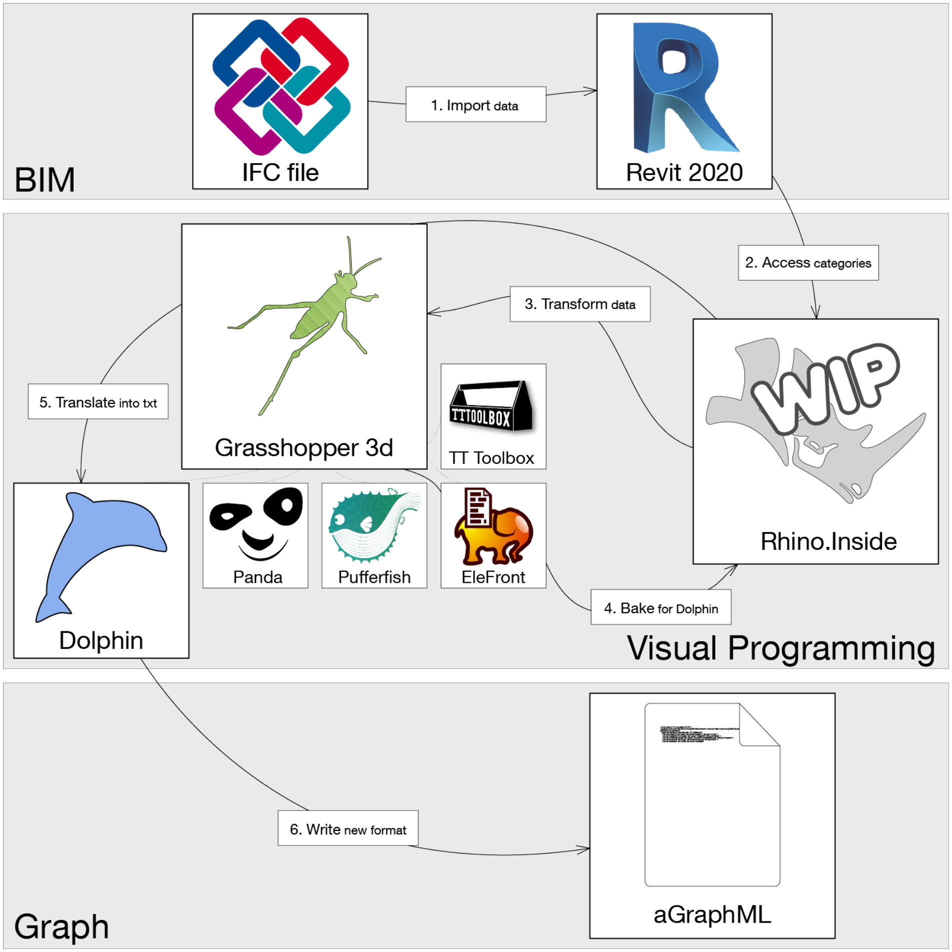
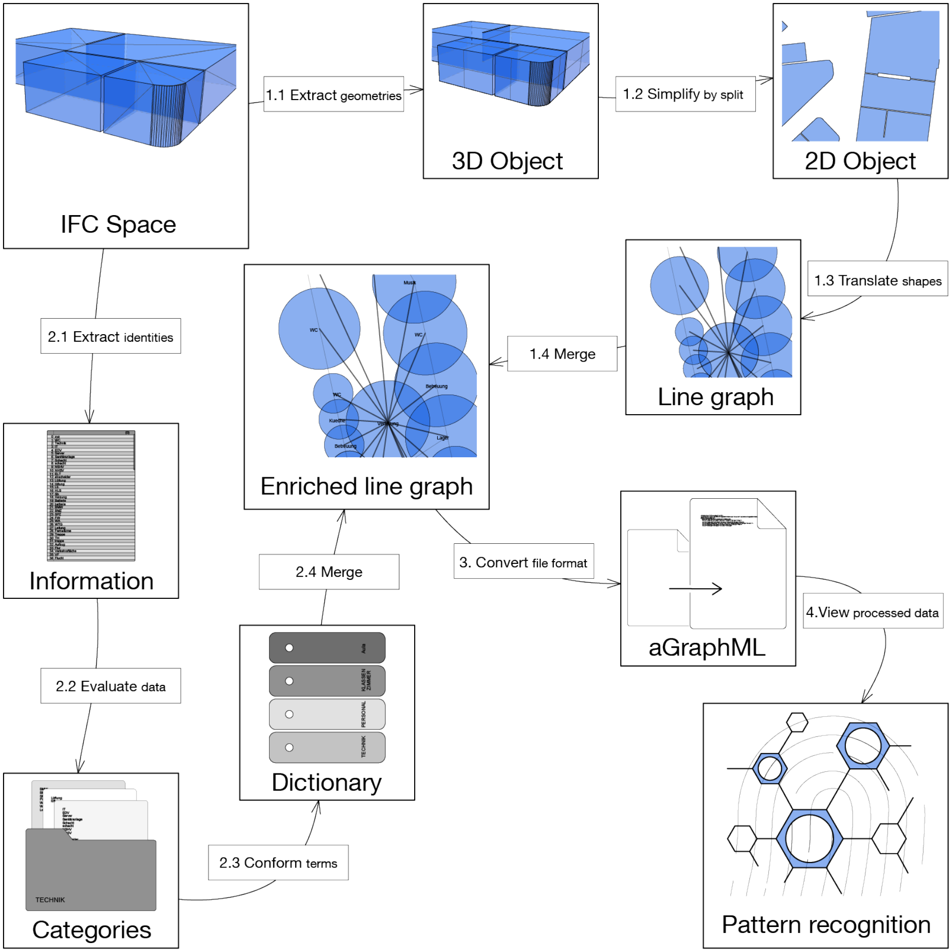


Figure 4
Overview and workflow through software programs.

open in REVIT. Working in Rhino3D offers to work with the parametric design tool Grasshopper for visual programming. Various plugins needed to be installed in Grasshopper, such as Pufferfish, TT Toolbox, Kangaroo2, Panda and EleFront, to transform the available geometries into readable shape language. Further, Rhino.Inside for Revit offers custom components, such as the Category.Picker, Elements.Filter, Category.Identity and Category.Elements. Used correctly, the chosen category elements show as ghosted objects in the Rhino window, as well as the REVIT main window, proving the real-time capabilities of Rhino.Inside. The plugin EleFront is used to assign attributes to the to-be-baked objects. Following, the Grasshopper plugin Dolphin, active in Grasshopper, is able to translate these shapes into the aGraphML format internally. This format then was printed as an XML file into the desired path.

Figure 5
Workflow of steps.



The first work step, as depicted in Figure 5, is extracting the relevant data, using the custom components of Rhino.Inside. The following tasks are simultaneously taken, but apart from each other. In order to create separated storeys as 2D Objects, meshes need to be transformed into Boundary Representations (Breps) and their base surfaces, grouped by the Z value and transformed into circles for readability by the Dolphin plugin. Afterwards, by using the appropriate list for the desired storey level, the chosen objects are isolated. In order to compare different floor plans of schools, the terminology of room names must be aligned. The research on the twelve buildings of 'Future school buildings' (Freireiss and Commerell, 2019) is used as reference to determine a dictionary. The different room names, assigned by different people, organisation, and of different times, must be interpreted by an architect and individually translated. At first the extracted data, represented in a list, needs to be categorised and then conformed under an overlying term. Text-matching is implemented, so keywords or partial words can be used to change the 'Room names' appropriately. Finally, the different categories are baked back into Rhino3D, merging the 2D objects and their conformed semantics, in order for the plugin Dolphin to read and convert it into aGraphML file. As a result a rough topological analysis was performed to identify structural patterns for school building as a basis to develop automatic machine learning approaches. For example, differentiating by names and ranking the sizes, as well as the amount of edges, using Gephi.

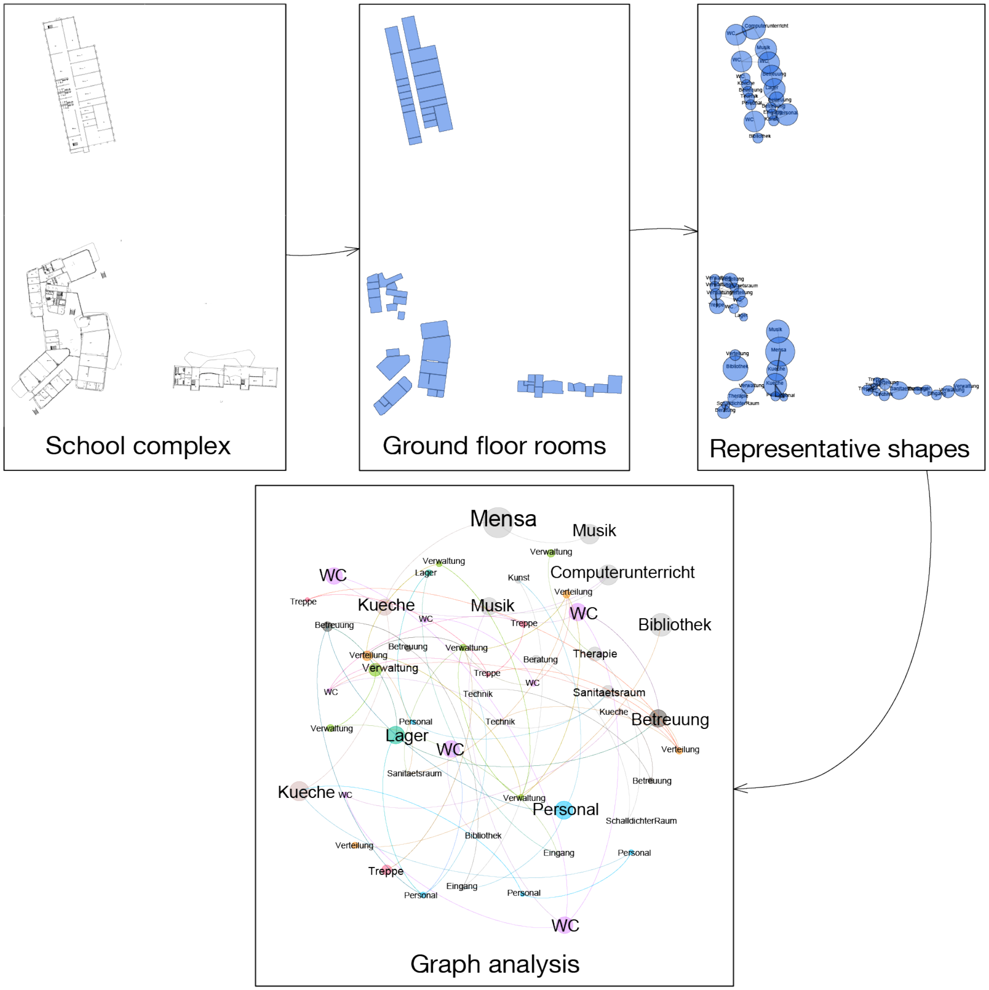
EVALUATION AND RESULTS

The described workflow and process in Grasshopper has been applied to IFC files of three different school buildings of the architect's office of ALN, Architekturbüro Leinhäupl + Neuber GmbH. Due to the testing with these floor plans, necessary conditions were depicted, improvements in the visual programming have been made, and finally, first pattern recognitions were conducted, using the created visual graph.

The Dolphin plugin has various restrictions, such as the representative room shapes of circles and that the interconnection between two circles cannot be more than one. Further, one circle cannot have more than one room descriptions. During testing, overlays occurred, as the interconnected points and room names are the centre of the circles. Improvements using the available floor plans, led to the development of an automated point correction.

The first tests showed satisfying and encouraging results (see Figure 6). After the automatic point-correction, the aGraphML files can be read, as well as the visual graph is well readable. The first pattern, recognised by the architects, is a correlation between space and size, such as the circulation area, which is very large and often connects or is itself a multipurpose area. As most of the floor plans include study clusters, it becomes clear, that the rooms open to students, are all quite similar in size and shape, but as the children can occupy all of them, the $4m^2$ per student are achieved. Further, the sequenced succession of rooms, starting at the 'Marktplatz' and ending in the classroom is evolving from a large common room alternating to a classroom through a passage-like small room, called 'inclusions', or a supervision room, which can be accessed from both adjoining classrooms. Gephi revealed that a classroom is linked with at least one other classroom. Group rooms are always connected to at least one 'Unterrichtsraum' (eng.: Teaching room), which is different from the classroom. Simultaneously, group rooms take up about half the area size of a classroom or equally sized 'Unterrichtsraum', thus providing the combined amount of space of 'Unterrichtsraum' and group room during project works, maximising the available square metre per student. Further, the ground floor of school buildings with more than two storeys is used solely for administrative and public rooms, such as library, cafeteria or first aid.

Figure 6
Development through the process.



FUTURE WORK

For further work, the Dolphin plugin is currently being improved. After the first developments, it recognises polygon shapes as rooms, simplifying the entire process of creating 'Wall' and 'Door' line representation and offering the ability to write the actual room edges, simultaneously solving the Boolean edge attribute of 'enclosed room'. Further, a new library for room terminology was created, so the 'Room names' are not converted, but 'Room types' can be recognised by 'Room name' and appropriately written. Finally, an edge representation for windows was created, as well as a Boolean option for 'Windows exist' edge attribute. The latest developments evolve around generic 'Exterior' Nodes and 'Entrance' edge types. The solution for this includes both improving the Grasshopper components of Dolphin, as well as visual programming using Grasshopper3D.

Finally, after more testing on a larger scale of floor plans, the pre-processed data is to be introduced to an artificial neural network to generate new architectural floor plans, using Deep Generative Modelling. An algorithmic setup issued to build Artificial Neural Networks to generate new data, based on the pre-processed data provided to the model, as suggested in Arora et al. (2020). This data can be used e.g. with a tensor data structure 'relation map', we propose in Eisenstadt et al. (2020) for intelligent variant generation, according to predefined design requirements and finally, an auto-completion of building designs.

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