URBAN GROWTH SIMULATION USING URBAN DYNAMICS AND CITYGML: A USE CASE FROM THE CITY OF MUNICH

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ABSTRACT:

Urban dynamics modelling using system dynamic (SD) approaches aims to provide an understanding of the major internal forces within an urban area, such as population development. SD models provide valuable information for decision and policy making. Urban systems are strongly related to the urban space, which is well described by geospatial data. Therefore, the connection of SD and geospatial data is advantageous, both for feeding spatial information into SD models and for further spatial analyses and for visualizing the results of SD in geographic context. This paper describes a new approach to combine an SD model with a semantic 3D city model. Our approach shows that a bidirectional data exchange between semantic city models and SD models improves the predictions generated by the SD models. Furthermore, we show that automatic modification of the semantic city model by the output of the SD model allows for 3D visualization and further analysis of future scenarios.
Since semantic 3D city models and SD models have complex data structures, and since the models have evolved in very different domains, integrating the models is a complex task. In order to facilitate the integration process, we developed a conceptual model, which describes the data structures of the semantic city model and of the SD model as well as the bidirectional relations between the models using the concept of model weaving. The approach was tested using the SD tool Vensim and a CityGML data set from the city of Munich for an urban densification use case.

1. INTRODUCTION

Today's cities are facing urban growth which affects the quality of life of its citizens. Elements of attractiveness become strained through the population rise. Therefore, understanding of the major internal forces controlling the balance of population, housing and industry of an urban area is the key to improve decision making. Understanding the interconnections of the system makes it possible to detect and simulate feedback loops (Collins et al. 1973) and (Schroeder et al. 1975). Since the system is strongly connected to the urban space, which today is well described by geospatial data (e.g. available land area, land use, buildings, transportation network, energy grid), it is of great interest to include respective data in system dynamics (SD) models in order to be able to make predictions as accurately as possible.
The system dynamics approach is used to describe the real world with a model which is applied to simulate the future development of a system. The complexity and non-linearity as well as feedback loop structures are taken into account in order to understand its social and physical processes. The simulation model consists of levels, rates and variables connected by equations (Forrester et al. 1992).
While stocks and flows models do not handle the spatial distribution of variables, Geographical Information Systems (GIS) can be used for spatio-temporal analysis, like visualization of population density per area or changes in land-use. To overcome the shortcomings of the stocks and flows on the one hand and GIS on the other hand several authors (Neuwirth et al. 2015) and (Zhao and Coors, 2012) have investigated the integration of GIS and stocks and flows models. However, coupling stocks and flows with semantic 3D city models has not been investigated yet. An extension to GIS applications are specific 3D city models using the international standard CityGML. The CityGML standard provides a representation of real life urban objects (Kolbe et al. 2005). Combining the stocks and flows concept with a 3D city model can support urban planning by simulating complex urban relationships, while at the same time providing a standardized approach to extract and store data.
In this paper we propose a novel modelling framework for coupling an urban system dynamics model using the modeling software Vensim with a semantic 3D city model, structured according to the international OGC standard CityGML. Our focus is the simulation of vertical growth of a part of Munich, referring to a scenario of land scarcity that requires densification rather than the new construction of buildings. The coupling of the models is bidirectional, i.e. the Vensim model uses information from CityGML as input and the results of the Vensim simulation flow back into the CityGML model. This allows for updating the CityGML model depending over time and visualize the 3D changes of the buildings. To be able to show the urban metabolism in a semantic 3D city model a use case is considered that combines different disciplines in relation to urban metabolism. These disciplines are from the field of population growth, urban planning and economic geography. The approach considers to develop a model that contains all the basic components of urban dynamics, based on a model of a paper from Joseph G.Whelan from 2001. This model is updated by initial values and attribute values from the CityGML data for

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Munich. A simulation of 20 years into the future is made. In the last step the CityGML data set is updated by output values of this 20 years of simulation.

The rest of the paper is organized as follows: In Section 2, the use case is presented. Section 3 provides the background on system dynamics, spatial system dynamics, and the CityGML standard, also the software packages Vensim and FME are described. Section 4 presents our concept for coupling urban dynamics and semantic 3D city models including a formal description using the Unified Modeling Language (UML). Section 5 demonstrates our concept by coupling the specific simulation tool Vensim and the connection to the semantic 3D city model using the geospatial extract-transform-load tool FME. In section 6 we present the implementation result and a comparison between a simulation considering the spatial dimension and one without. Section 7 concludes the paper.

2. USE CASE

Many cities are facing substantial urban growth and they are thriving. The strong growth of a city is mainly due to the interaction of in-migration and the importance of a city as a business location.

If more jobs are generated in a city i.e., by the construction of new business structures, more people move in and vice versa. If more people move into a city, companies can generate more jobs. The population is constantly growing and so is the demand for housing and business structures. Accordingly, all the aspects that were mentioned before are influencing each other. Whelan, 2001 describe a city life cycle by three periods, which is characterized by a period of economic growth followed by a period of transition toward equilibrium:

1. Growth period, business activity is expanding, while the unemployment is low. The “Population” and the number of “Business Structures” grow quickly. The city appears to be economically healthy.
2. Transition period, pressure is rising and the city conditions become worsen which slow further growth. Business structure construction rate becomes smaller. Therefore, the rate of inn Migration” into the city decrease.
3. Equilibrium period, the population and business structure number stop growing. As a result the city starts to suffer from high unemployment problems.

The city of Munich has a rapid urban growth recently. In an area around the “Deutsche Museum”, there is just one possibility for the city to grow. In the chosen district there is a scarcity of areas that are free for construction of buildings. This scarcity is so high that there are simply no more existing available land areas. That leads to the necessity of densification. Since growth is not possible in a horizontal way, it needs to happen vertically.

3. BACKGROUND

3.1 3D models and urban densification

Different approaches for urban modelling with focus on identifying locations suitable for vertical densification have been developed by researchers. iCity 3D is a method and tool that was developed by Koziatk and Dragivevic in 2017. It aims to represent vertical urban change over time and includes a land suitability analysis for urban densification as well as the generation of 3D buildings using the ESRI City Engine Computer Generated Architecture (CGA) language (Koziatk and Dragivevic 2017). Seifert et al. (2020) present a software framework called “The Urban Strategy Playground” supporting decision making processes and public participation. The framework allows urban planners and stakeholders to develop strategies for urban densification. Furthermore, it provides tools for monitoring building codes, analysis of key density indicators and green space provision, simulation of shading, as well as building energy and noise dispersion. In another study Seifert et al. (2016) present a method that provide an automatic transformation of CityGML building objects into a parametric representation. The researchers show the usefulness of parametric modelling in supporting urban planning and simulating building regulation.

Luo and He (2016) presented a study that concentrates on the advantages of the Software ESRI City Engine for urban modelling. Their study provides a comparison between City Engine procedural modelling and conventional modelling. The study concludes that City Engine is more suitable for city modelling compared to conventional modelling software, since it provides a communication platform for public participation and can be combined with other simulation tools to support urban planning and management.

The studies described above have in common that they use 3D models for urban densification cases, but a coupling between semantic 3D city models and SD models is not yet described in any study known to the authors.

Our approach contributes to closing this gap in research. Despite the complexity that comes with integrating SD models with semantic 3D city models, a bidirectional exchange of information between these different types of models promises an improvement in the creation of future urban densification scenarios. We base this assumption on the fact that SD models can represent complex socio-economic relationships to be considered in urban development better than the approaches described so far. In addition, information derived from semantic 3D city models can inform SD models about development opportunities and constraints arising from existing urban structures, thereby improving predictions.

3.2 System Dynamics and Spatial System Dynamics

One approach for modelling urban dynamics is the concept of urban metabolism, which compares urban areas to living organisms. It is used to quantify inputs, outputs and storage of energy, water, nutrients, materials and waste as well as people, land, capital and information (Kennedy et al. 2011, Schmitt 2015). Urban metabolism can therefore serve as a basis for sustainable urban design and policy analysis (Kennedy et al. 2011). Urban metabolism can either be implemented as static stock and flow analysis (e.g. material or energy flow analysis) or as a dynamic stocks and flows model (Schmitt 2015). Both stocks and flows approaches can help to break down the complexity of urban areas and support decisions concerning urban planning and design (Schmitt 2015). Some areas of application are the identification of main sources of greenhouse gas (GHG) emissions, calculation of the sustainability of a city according to certain indicators and determination of the potential for building material recycling. Urban dynamics models in particular simulate the major internal forces controlling the balance of population, housing and industry within a city or urban area. The approach is applied to describe interrelationships (economic, political, psychological, sociological variables), the long-term evolution of urban areas including positive and negative feedback-loops and it provides a formal means for policy making. Urban dynamics can be used to improve the quality of life in cities and support the ability to make appropriate decisions (Collins et al., 1973).

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Spatial system dynamics is an extension of the system dynamics approach by including spatial data. The advantages are exemplarily shown in the paper of Neuwirth et al. (2014). A fictitious environment called Daisyworld is applied to illustrate the connection of system dynamics and GIS. It represents the balance of a dynamic landscape driven by temperature changes which are caused by varying luminosities of growing black and white daisies. A comparison with non-spatial systems reveals the importance of considering spatio-temporal feedbacks. The spatial system dynamics approach takes into account initial spatial data and exhibits a higher robustness with respect to realistic predictions.

3.3 Semantic 3D city models - CityGML

Semantic 3D city models are virtual models of the urban environment, i.e., datasets representing physical reality entities such as buildings, streets, trees, bridges, and terrain. Unlike virtual reality (VR) models, they are structured (e.g., subdivided and assigned) according to thematic and logical criteria rather than graphical or rendering considerations. The objects of a semantic 3D city model represent the respective real things with their thematic, geometric, topological and radiometric properties. In addition, logical and spatial relationships between different objects are expressed (Kolbe & Donaubauer, 2021).

CityGML is an international standard for an open data model and XML-based format for the storage and exchange of virtual 3D city models. Aside from the virtual 3D representation of city objects and their topological relationships, it includes semantic information to allow for thematic queries, analysis tasks and spatial data mining (Gröger et al. 2012).

Since CityGML is a common semantic information model, it can be used for different application areas like urban planning, disaster management, environmental simulations, or navigation and many more. CityGML is to be seen as a modelling framework with the aim of reaching a common definition of basic entities, attributes, and relations of a 3D city model. It is therefore possible to reuse data in different fields of interest and share data between different applications. CityGML includes a spatial model, which defines the geometrical representation, an appearance model, that defines textures and materials, and a thematic model, which represents the most important urban objects by a set of predefined object classes. The thematic modules which are important for this research paper include: Building, LandUse, CityObjectGroup, and Generics.

The Generics module can be used to extend predefined object classes by generic attributes or to extend thematic modules by generic objects, which allows to represent real world entities or properties of real world entities that are not represented by the predefined attributes or object classes. Another way of adding additional objects and attributes to CityGML is possible through Application Domain Extensions (ADEs). This is especially useful for the modelling of more complex objects and relationships, in case the generics module does not provide enough possibilities for their representation and allows to formally describe the extensions using UML/XMLSchema. Several CityGML ADEs have been developed to date. For the modelling of flows and live data the Utility NetworkADE and the Dynamizer ADE are of particular importance (Kutzner et al. 2020). However, the work presented in this paper and in particular the UML model presented in section 4.2 will provide a first step into the direction of a new ADE for linking semantic 3D city models and urban dynamics models.

3.4 Software framework for coupling Urban Dynamics and semantic 3D city models

3.4.1 Vensim

Vensim is a simulation software which offers many features in order to model real systems and predict their behaviour and future development. In this project the software is applied for defining a basic urban system which allows the simulation of city growth (Vensim, 2022). Further, Vensim PRO allows to introduce external data which is needed to build the connection with the spatial data from a CityGML data set. Exporting the simulation results in Excel format is supported by the software as well, which is needed for updating the CityGML model with respect to time.

A Vensim model mainly consists of four different components which are marked in the example in Figure 1:

1. Levels: Consist of the total number of a quantity and accumulates or depletes over time
2. Rates: Are the rate of change of a level
3. Arrows: Define dependencies of individual components
4. Variables: Are constants or equations which influence each other or levels or rates

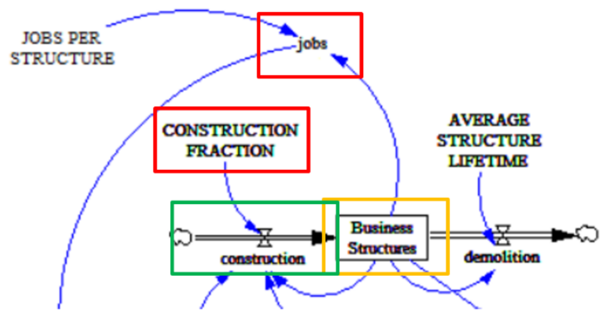

Figure 1: Components of Vensim model (Level in yellow, rate in green, arrows in blue and variables in red)

3.4.2 FME

The Feature Manipulation Engine (FME) is a data integration and manipulation software package that can process spatial and non-spatial data (FME, 2022). In this project FME is used to integrate and manipulate CityGML data until a result is built that can be read by Vensim containing all the information that is necessary. It provides a mechanism to create an interface between CityGML and the Vensim Model.

4. COUPLING URBAN DYNAMICS AND SEMANTIC 3D CITY MODELS

4.1 Methodology

The basic strategy in this paper is to design a model that uses the advantages of the system dynamics approach (studying a complex system based in feedbacks rather than linear relations) combined with the advantages of semantic 3D city models (representation of the geographical dimension of elements, in a way that both spatial and temporal dynamics can be monitored). In this paper, the conceptual model is technically implemented for the use case of urban growth. The basic components of our approach are as follows:

Structural change model: the structural change model is composed of two main parts. The first part is concerned with modelling the spatial structures with regard to a qualitative

change of spatial objects as, for example, a change in land use from one type to another. This can be modelled using regular stocks and flows modelling tools. However, the second part is the process to interact with space and leads to changes of the structure in a particular spatial environment. In current SD models the feedback elements are non-spatial and expressed in quantities (numerically).
In the case of urban growth increasing the number of commercial structure will lead to an increase of the available jobs and therefore an increase of the number of people moving to the city. This will lead to an increasing intensity of the building housing structure. The city becomes more crowded. However, this affects the quality of life in the city. The developed framework provides an intermediate tool to manage the interaction.

Establishing semantic links between objects of the semantic 3D city model and stocks and flows elements: There is a need to establish semantic links between stocks and flows in the SD model and the semantic 3D city model representing the physical environment. The stocks represent the size of specific spatial objects (structural elements), e.g the area of the land. In addition, stocks can be physically updated based on spatial allocation rules, e.g., by constraining spatial extent vertically rather than horizontally, i.e., by creating additional floors for existing buildings. For many applications the growth of an area or object is based on the zoning restriction on this area. It is important to consider that the association between a stock in the SD model and the objects in the semantic 3D city model might be a one-to-many rather than a one-to-one relationship. For example, the stock "industrial land use" may be related to several sites in different locations. The stock could be related to multiple, non-adjacent zones and regions. Therefore, there is a need to exchange the feedback loops between spatial objects and their stocks and flows in the system dynamic model.

Establishing a bidirectional data exchange between the models: The final step in the methodology is to couple the semantic 3D city model and the SD model on the level of bidirectional data exchange between the models. The aim of the approach we developed is to use loose coupling. This means that the models should reside in their domain specific ecosystems, like geospatial database systems for the semantic 3D city models and simulation software for the SD model. However, there must be a well-defined data structure that allows for the models to communicate and exchange data in a bidirectional way.

4.2 UML class diagram as a formal description of bidirectional data exchange

The connection between the semantic 3D city model and the urban dynamics model is described on a formal, software platform independent level using a UML class diagram. The UML diagram in figure 2 is composed of three main parts:

On the left side of the UML diagram, the semantic 3D city model is presented using a static structure. As mentioned before, CityGML offers information about city objects like buildings which includes their geometrical shape and position but also thematic information like the usage type and the number of floors of the buildings. CityGML also defines land use objects, which allow to derive the amount of existing building structures and to differentiate between housing and industry (or other types of land use).

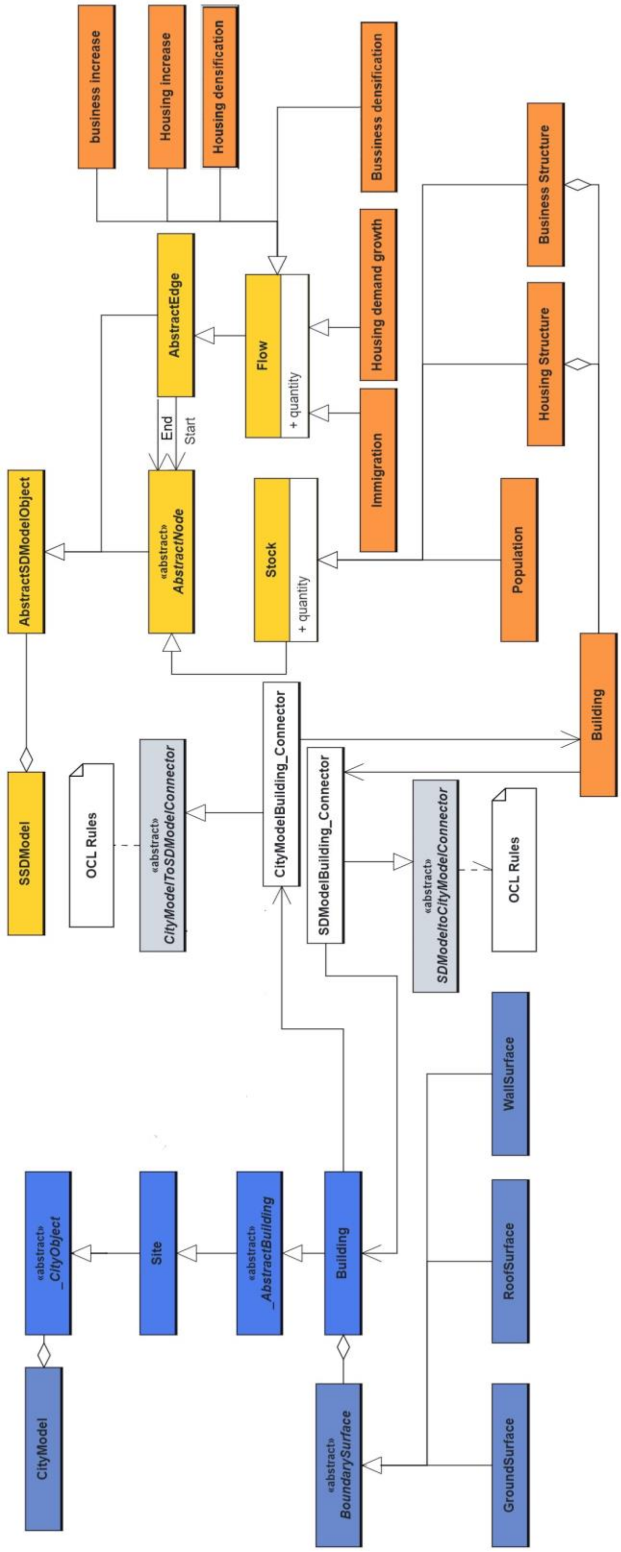

Figure 2: UML class diagram defining a data structure for a bidirectional data transfer between semantic 3D city model and SD model

On the right side of the diagram, the typical data structure of an SD model is described. The goal here is not to describe the internal structures of the SD model with all the mathematical formulas, but to describe the data structure necessary for bidirectional data exchange with the semantic 3D city model.

SD models are represented by a graph structure consisting of edges and nodes, where edges represent the flows and nodes represent the stocks. Both models contain abstract classes, which describe application independent concepts. Application specific classes are derived from these abstract classes by specialization relations, i.e. for this use case of urban densification the following specific classes are derived from the abstract class for stocks: Housing structure, Population, Business structure. For flows the following specific classes are defined for our use case: housing demand growth or immigration.

The so-called weaving model is shown in the centre of the diagram. It formalizes the bidirectional exchange of data between the semantic 3D city model and the SD model. It is composed of two main classes CityModel-ToSDModelConnector and SDModelToCityModelConnector. The first is used to extract the required objects and attributes in order to have an appropriate input for the SD model. The respective constraint on the objects and their attributes are expressed using the object constraint language OCL (named "OCL rules" in the diagram). Using OCL rules, the buildings that correspond to a specific use type are extracted and the total number of inhabitants from all the buildings in a specific area is derived. The resulting data contain the total number of inhabitants and the number of floors for each building separated according to the building type (housing, industry). In the weaving model the class SDModelToCityModelConnector is responsible for moving the result of one simulation step to the spatial model by applying the attributes to update the CityGML building objects. Accordingly, the geometry of the objects must as well be updated. Thus, the CityGML attribute "measuredHeight" is changed for each building according to the new number of floors. Also the geometry of the Building objects needs to be changed to reflect the new building heights. In a CityGML LoD2 model this can be done by extruding the building footprints to the new height value, and deriving updated WallSurface objects from the extruded geometry. Additionally, a corresponding vertical offset must be applied to the RoofSurface objects.

5. PROOF OF CONCEPT

5.1 SD Model implemented in Vensim

The SD model we implemented using the software package Vensim is based on the urban growth model introduced by Whelan (2001). The model presented in this paper consists of the stocks "Business Structures" and "Population". Dependencies between the stocks are drawn by variables related to labour availability and labour force. We extended this model by the stocks "Housing Demand" and "Housing Structures" which as well play a fundamental role in the dynamics of an urban system. Further, these stocks are closely related with geospatial information which is our focus in this project. All the stocks quantities in the diagram below were extracted from geospatial data representing real world on the level of individual buildings, i.e. the number of floors for each building and to distinguish the buildings according to their use (industry or housing). Furthermore, the total number of inhabitants can be derived from the CityGML model. Approaches on how to connect the stocks could be found in Xu et al. (2011). The Vensim model is shown in figure 3.

The model considers "jobs" as the motivation to the people who plan to move into the city and as an important factor to retain its residents. Success of investment demonstrates potential for population growth and increase in the profitability of construction of "business structure". Therefore, further development occurs as a result of urban development and business expansion. The continuous availability of land during the growth stage allows business construction to keep pace with the increasing population, so people continue to be motivated by the job opportunities in the area. The construction of new business structures will generate more jobs in the city. Companies generate more jobs to meet the demand of an increasing number of people moving to the city. The population is constantly growing and so is the demand for "housing" and for "business structures". Whelan (2001) describes the city during the growth period "… the city appears to be economically healthy: business activity is expanding and unemployment is low. The 'Population' and the number of 'Business Structures' grow quickly". However, Whelan (2001) indicates that during the transition period, the conditions become less desirable which leads to slow down any further growth. The "Construction" rate of "Business Structures" becomes lower, and so does the rate of migration into the city.

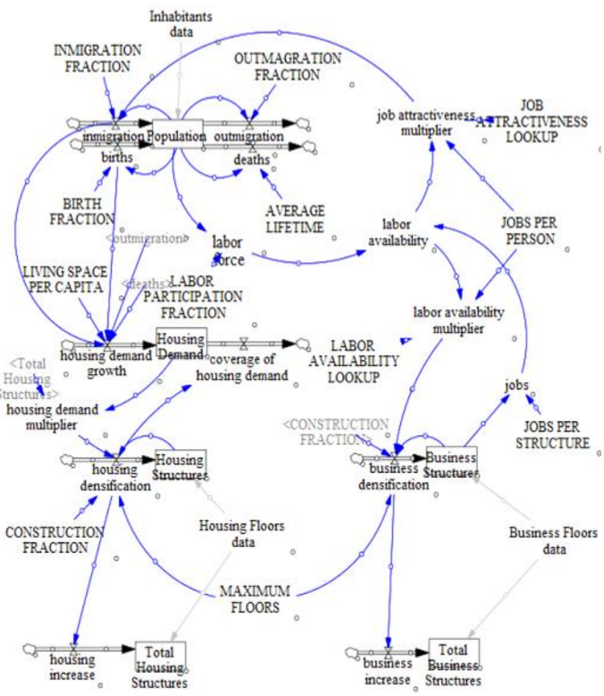

Figure 3: Spatial system dynamics model simulating urban growth

When the "Population" and the number of "Business Structures" stop growing, the city suffers from problems such as high unemployment, because the increase in labour availability does not match the decline in job availability. This leads to high unemployment rates which discourage people to migrate to the city.

In the beginning, the labour availability is a due to the increase in population and business structure, in middle stages labour availability declines slightly (in other words, job availability improves slightly), jobs become less available to the average job seeker (labour availability starts increasing). In the final stages the lower availability of jobs occurs because the number of jobs begins to rise slower than population growth, once the land area decreases and slows down business construction.

The constraint of a fixed land area limits growth by making additional construction of business structures less and economically unjustifiable. The model reaches equilibrium when the constructing equals to the demolition of business structures.

5.2 Bidirectional Data Exchange using ETL processes

In order to establish the bidirectional data exchange between the system dynamics model and the semantic 3D city model, the platform independent UML model has been translated manually into ETL processes based on the spatial ETL software package FME. Figure 4 provides an overview of the interaction mechanism. The ETL processes shown in figure 4 are providing synchronous data flows between SD and CityGML. The SD use the data extracted from CityGML and then after one step of simulation the CityGML model gets updated. The tools are representing the weaving part of the UML model in section 4.2. It is working as a synchronous operation loop, exchanging data between SD model and CityGML model.

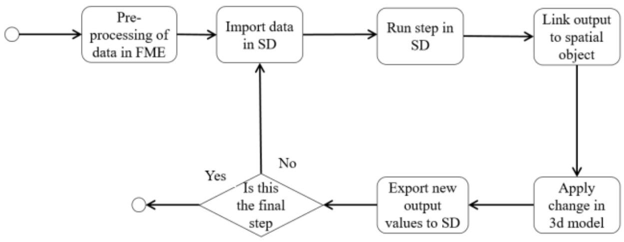

Figure 4: Diagram showing the interaction between Vensim and FME software package

5.3 Simulation Results

The implemented urban growth model in Vensim is tested in order to investigate if the simulation leads to reasonable results. Figure 5 shows the predictions for population growth. The base run (blue curve) displays a constant increase of inhabitants. The scenario of high construction (green curve) is applied in order to see what happens if the densification of housing and business structures reaches its limits. It can be seen that the population growth is stronger, due to more available building structures which in turn increases attractiveness and thus the in-migration. Indeed, this growth converges to a maximum. This means that all buildings have been densified and no further increase in population is possible. The red curve represents simulation without considering information from the semantic 3D city model. Since their constraints arising from existing urban structures are in this case not known to the SD model, population increases to infinity.

Figure 6 displays the total amount of floors for housing and business structures (top) as well as the floors of an individual building of each category (bottom). Again, it can be seen that the buildings reach a pre-defined maximum number of 10 floors after a certain time and thus limit an infinite growth. This means, the model is working as expected. It is also important to check whether the model is adjusted correctly. Therefore, the results are compared to external statistical predictions. It has to be noted that a direct comparison is complicated as the feedback loops of the simulation model lead to continuous changes of the rates of population and housing demand growth. Additionally, the model is applied on a specific inner district of Munich instead of the whole city. Thus, the comparison with statistical data has to be seen as an orientation rather than exact specifications.

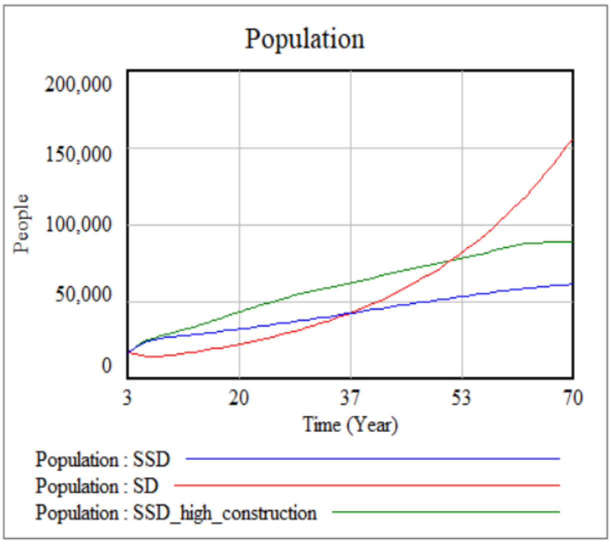

Figure 5: Simulation for two scenarios with respect to the population growth.

The Bayerisches Landesamt für Statistik (2020, Bavarian federal office for statistics) offers a 20 years prediction of the population growth of the districts of Munich including Munich. They predict an overall population growth of 7.8 % per 20 years for the whole region of Munich. By looking at our base simulation in Figure 6 a rapid growth at the beginning can be seen. The curve may need to stabilize first which may be the result of an inconsistency of the initial values especially with respect to the Housing Demand which was selected to be 0. However, the simulation stabilizes after the first years. It then shows a linear growth of more than 30 % per 20 years which is much higher than the statistical reference. Our constants for in- and out-migration with 8 % and for birth and death rate with 1.5 % may not be the reason for such high prediction values as they balance each other. But the resulting population growth rate is indirectly affected by the availability of housing and business structures. This in turn is driven by the construction rate.

A lower rate would therefore improve the results for Munich. Furthermore, the statistics of Bavaria show a stagnation of the population growth already after around 15 years. This could be reached by allowing less buildings to grow and by lowering the number of maximum possible floors. Including information on building permits would therefore be a reasonable extension of the urban dynamics model.

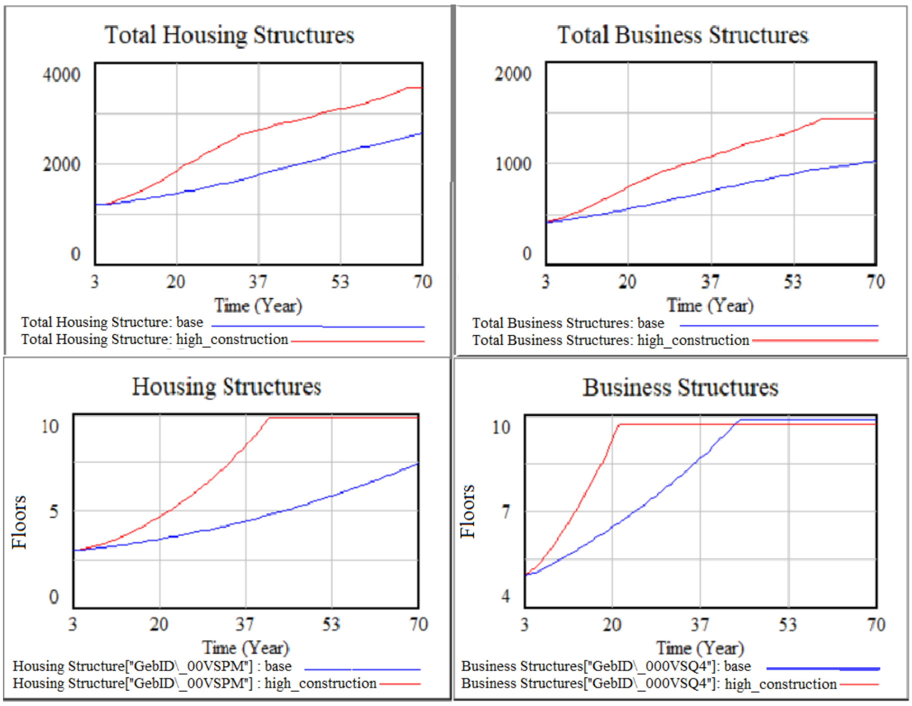

Figure 6: Simulation results for two scenarios with respect to building structures

5.4 Updating the semantic 3D city model

Our approach not only uses the geospatial data from the semantic 3D city model as input to the SD model, but also enriches the 3D city model with the output generated by the SD model. This results in changes to the city model both at the level of thematic attributes and in terms of the geometry of the objects. The following figure 7 shows building objects from the original 3D city model.
The model was enriched using FME with simulation results to represent a scenario 20 years in the future. As shown in Figure 8 the buildings storeys have increased by one or two floors. That extension of storeys is shown in the visualization.
The visualization demonstrates that especially the geometry of the 3D city model was successfully updated. Further, it can be seen that buildings which are not used for housing or industry stay unchanged (e.g. a museum that exists in our study area). The 3D visualization is not only useful for validating the results but also offers the possibility of investigating how urban growth affects the city spatially. The results could be applied for studies with respect to visibility, noise, energy, etc. which strongly supports decision making within a city. As we use CityGML as a standardized data structure, simulation and analysis tools as described in Yao et al. (2018) could immediately be used for evaluating future scenarios generated by the SD model.

6. CONCLUSION AND OUTLOOK

The integration of spatial data from CityGML in an urban dynamics simulation model required the implementation of several processing steps. As a basis the simulation of vertical growth of housing and business structures with respect to population growth and labour availability was achieved by defining an urban dynamics model in Vensim. In order to establish a bidirectional data exchange between CityGML and Vensim, an intermediate data structure has been developed and described independently of a specific implementation as a UML diagram. Extract Transform Load processes were implemented based on this data structure using the FME software package.
The required data from CityGML could be extracted with FME by connecting buildings with land use. The data could be included in Vensim and an exemplary growth of 20 years was simulated. Overall, the simulation led to expected results, however in comparison with external statistical data it could be derived that the population growth of the model was too strong. This can be improved in future by lowering the construction rate or reducing the number of buildings which are allowed to densify. Finally, the CityGML model could be successfully updated according to the simulation results again by using FME.
Our work shows that an integration of geospatial data from semantic 3D city models in urban dynamics is possible and can improve predictions as results shows in the previous section. The integration of initial values from external data is advantageous as it brings the simulation closer to reality. Furthermore, the 3D visualization could be used for spatial investigations which supports decision making.
In our example only CityGML building objects have been considered. Future investigation should include other feature types, which would allow to account for aspects like mobility and the provision with energy and fresh water in an extended SD model. The basic Vensim model and connection with CityGML allows several extensions. As suggested before the integration of building restrictions, e.g. due to monument protection, would be reasonable and could bring the results closer to the statistical references. Further, the demolition of buildings must be taken into account especially for longer simulation periods. This would also need the integration of the possibility of new construction on available land area. Generally, the urban growth model could be extended according to other use cases or cities. CityGML proved to be a valuable

source for urban analysis and simulation, it can provide diverse information about the built environment. Finally, it should be verified to what extent the intermediate data structure meets the requirements of further use cases and simulation tools other than Vensim. Also, a rule-based generation of executable code based on the weaving classes would be a useful addition to our approach.

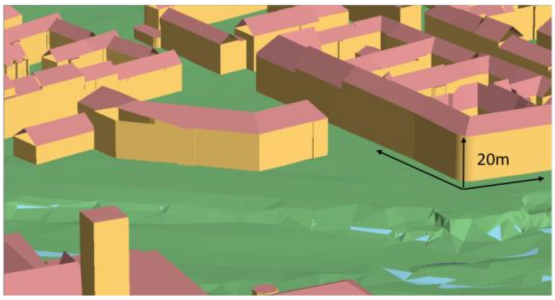

Figure 7: CityGML model representing the current state of the city.

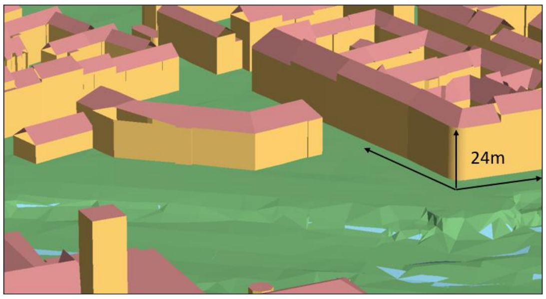

Figure 8: CityGML model representing a future urban densification scenario (buildings are extended vertically).

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