System Dynamics Libraries - An approach to develop modular-oriented simulation models

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Abstract

Simulations are well established in a variety of areas, e.g. business studies, natural and political sciences. Purpose of such simulations is, among others, to explore dynamic structures, to support the understanding of complex relationships and to improve systems thinking. The aim of this paper is to introduce a module-oriented development framework for domain specific system dynamics libraries (SDL approach), which can be used in the simulation of dynamic relationships on different levels of an industry, as an example the construction industry. This approach enables multidisciplinary teams to develop joint models from varying perspectives. Compared to other fields, significantly less implementations of dynamic simulations exist in the construction industry. This work demonstrates the desire to expand the system dynamics field into the construction sector. Therefore, the SDL approach provides a valuable contribution to promote further developments, e.g. the explanation of the risk situation of a company, the identification and evaluation of project risks, endangered operational procedures on various functional levels or to improve systems thinking and the understanding of the decision making process in detail. Regardless of the construction industry, the introduced approach can be used in any kind of business, independent of decision level and functional area.

Part I

Introduction

This part will briefly explain the general background and the motivation for developing the SDL approach. However, this paper does not claim to offer a comprehensive and highly detailed overview of all related issues, but aims at introducing the relationships and make them available for the reader. If the reader is interested in gaining more details about specific topics, the author suggests to have a closer look into the cited literature within the paper. The author also welcomes personal feedback and dialogue.

1 System Dynamics in the field of construction

The System Dynamics (SD) approach became particularly widespread in the 1980s in such fields as project management, shipbuilding, defense and aviation (Roberts 1978, Cooper 1980, Reichelt & Sterman 1990). Simulation is not just an academic exercise today. Therefore there are numerous SD-models in the various fields of stationary industry that are largely universally transferable. According to Bauer, the special feature of the construction industry is that it is a processing industry without own production site. The buildings are made in make-to-order production at a requested location (Bauer 2007) and various stakeholders are involved. Because of the one of a kind production in the non-stationary industry, the transfer of existing models from the stationary industry proves difficult. John D. Sterman also acknowledged this distinct feature of the construction industry in the 90s and related it to the SD approach. According to Sterman (1992), construction projects are highly complex and dynamic and consist of numerous interdependent elements, various feedback loops and non-linear relations and feature both "hard" and "soft" data.

Irrespective of the different research areas construction engineers are working on, a set of established methods and procedures can be observed in the construction practice. These methods and procedures are based on research findings and norms or have been transferred and adapted from other fields; the long-term effective ones form a code of practice readily available when needed. This fact should be taken into consideration when applying methods from other domains.

Although many researchers apply the SD-approach to problem-solving in the field of construction (e.g. Chang et al. 1991, Ogunlana et al. 1995, Ibbs & Liu 2005, Mbiti 2008, Mawdesley & Al-Jibouri 2010, Skribans 2010, Hou et al. 2011), there is currently no systematic approach to make the design of SD models practicable and applicable on the one hand, and to support the universal usability of construction-specific models on the other hand.

The obstacles frequently encountered when attempting to introduce or apply simulations in the field of construction, prove the necessity of such a systematic universal approach. An empirical study (Study SimBauDE: The current use of simulations in the German construction industry, carried out by the author in the year 2012) identifies these obstacles as lack of know-how, excessive costs and the increased effort associated with the application of the model. Hence, a readily applicable modeling approach would be helpful in both closing the gap between existing knowledge and the expertise required by the simulation and in reducing the modeling costs. Such an approach is not only justifiable by the mentioned obstacles it is supposed to overcome, but also by the fact that most test subjects would consider making increased use of simulations in their companies, extending the field of application of the approach beyond the usual field of research and development. Further, the approach appears especially promising in the management of organizational strategy and human resources. Here, the simulation is mainly regarded as a method to cut costs and minimize potential risks. Despite the few basic elements it consists of (stock- and flow values, variables, auxiliary variables, constant variables), the SD approach seems to be seen in the literature as well as in its applications more as a "special method". The design of a specific method and of a feasible framework for the modeling and simulation of dynamic systems can contribute sensibly in this context, as it provides a purpose-oriented, useful and immediate access to system dynamics simulations within a domain.

2 Motivation and aim

Even though SD models are used in various fields of science to gain more insights, both theory and practice of theses simulations are rather difficult to comprehend for externals or third parties without previous SD knowledge. The SD approach may be well-known in many branches of science, but for a comprehensive discussion – for instance to be able to develop valid and functioning models and simulations independently – both a detailed and thorough study of the theoretical relationships and an intensive search for previous models, which are potentially suitable for integration into the intended model, deems necessary. In addition to that, previously developed SD models quite often acquire their reputation within their specific area of a single domain only. Currently it appears to be inevitable that previously existing models (independent of their scientific subject) and their contained elements can hardly be integrated into new models. One significant reason can be the lack of a viable possibility to exchange existing SD models within a domain or even beyond it. This seems to point to the necessity to develop a general and feasible method to classify SD models as well as their contained components and units to make them available for other modelers. As both human resources and financial expenses required for the development and implementation of simulations can be quite substantial, it appears sensible to support one of the most complex phases in developing a simulation – the modeling. One possibility is the development of domain-specific libraries of simulation models, called system dynamics libraries in the following. Especially in this context, the development framework for system dynamic libraries (SDL) offers the following advantages:

- A specific problem-oriented simulation model can be easily designed through combining allready existing entities out of the SDL.
- Especially new, interested but so far unexperienced simulation designers will gain a direct access to the modeling process without the necessity to deal in detail with the theory first.
- A module-oriented model allows the design of variable and versatile simulations. Hence, the developed simulations are reusable for other problems by adjusting, adding or reducing the model.
- Such simulations can be executed on the basis of the complete modeled reality depicted therein or part of it.
- Due to the reason, that different simulation models will have a common basis, insights gained from one simulation scenario can be applied to another simulation scenario and vice versa.

Consequently, the development of an SDL offers considerable and numerous possibilities of application. This, in turn, results in the following central aim of this paper:

The aim of this paper is to introduce a method with which the reader will be able to develop module-oriented simulation models, which can be used in the simulation of multi causal and dynamic relationships on different industry levels as well as in research, academic education and further training and practice. The intended audience is both the academic and the practitioner.

Part II

Module-oriented modeling approach

The aim of this part is to introduce the approach for modular simulation models. In doing so, the models should be designed in a modular way, to flexibly allow for further developments. Building on separate components, a library will be set up, allowing for new elements to be embedded in it or for the existing ones to be adjusted or extended respectively. For the simulation this is meaningful in two ways: insights can be gained both from using a single element and from the sensible combination of several interacting elements. This fact should also support the design of different simulations, in which distinct components can be sensibly combined in modules, following the logic of gaining knowledge.

3 System Dynamics Libraries

Regardless of existing approaches to establish a system dynamics library (ref. Hines (2005) or Tom Fiddaman's System Dynamics Model Library, ref. http://www.metasd.com/models/), the reader will see, that the introduced approach starts at a more fundamental level. Following the nomenclatura of chemistry, a system dynamics library (SDL) is based on an atom-molecule-component-approach (abbreviated: AMCA). Therefore such a library consists of the following three fundamental entities (E): Atom (a), Molecule (m) and Component (c). In contrast to the nomenclatura of chemistry the term molecular substance is not used here.

An atom is the smallest entity (Nic et al. 2006) which can still be characterized in a model. To these units belong all single entities which exist independently and without external influence inside a model. Following general model theory, atoms have defined attributes and properties (Stachowiak 1973). Atoms cannot cause system changes by themselves only, but may do so in combination with other entities existing in a model. Consequently, all discrete entities are atoms, e.g. stock and flow variables, (auxiliary) variables and constants. A coupling of atoms forms a molecule (Nic et al. 2006), which gains its properties through the interaction of its atoms. The linking of molecules results in a component or a module which has a case-sensitive internal processing logic. The combination of atoms, molecules and components results in a comprehensive model. As the application of system dynamics models is supposed to lead to more consolidated decisions and decision-making rules (Forrester 1961), the decision-making level (D) is included as well in the approach introduced here. Therefore the operative, the tactical and the strategic decision-making level are equally comprised. The operative level contains mostly the physical realization and the implementation of tasks. On the tactical level, the processes and the organization within a corporation play a central role whereas the position and the targets of the corporation in the market are central focus of the strategic level.

To derive effective decision-making rules for various functional areas (F) within a company with the help of a holistic system analysis of complex dynamic problem settings, it appears sensible to include the following areas: strategy and organization (SO), research and development (RD), finance and governance (FG), marketing and sales (MS), human resources and leadership (HL), as well as operations and procurement (OP). The structure of the functional areas follows van Assen et al. (2011). With the help of such a system (figure 1), different SDL can be developed on the basis of the SD approach. These libraries offer a helpful transfer potential for their own domain, but also make units available beyond their own domain and allow

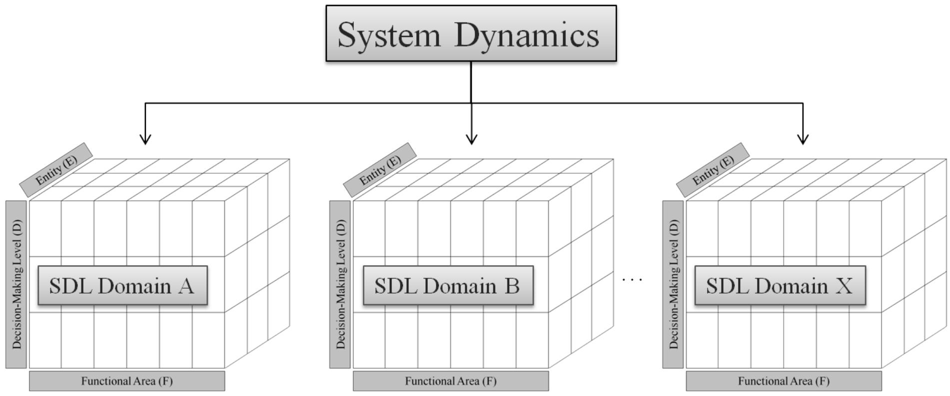

Figure 1: Concept of System Dynamics Libraries (SDL)

the integration in their branch of science with little or no adaptations. This classification of units creates a high degree of universality and reusability. Previously developed entities for a specific decision-making level or functional level can be used in other levels with potentially little or no adaptations.

Using this approach does not only mean that new entities in development can be classified systematically, but existing models (independent of the domain they were developed for) can be analyzed methodically, the separate entities can be extracted and made available in a specific SDL. Thus, an SDL can be continuously complemented by controlled and systematic examination of SD models.

Atoms and molecules represent the universal entities in an SDL, whereas components were already assigned a fixed point of reference within a precise problem setting in a specific level. The boundaries between the different levels can be blurred, depending on the selected system limitations and the desired scale. If, for example, a company is modeled as a whole on the strategic level, considering details or individual processes of the work flow deem inappropriate (Troitzsch 2004). In this case a molecule or a component, which was developed in detail for the operative level, can be reduced to an atom in a model of the strategic level. Here, the attribute required for the new model will be derived as a time-dependent function from the previous entity. If the need to inspect the behavior of this atom in more detail is identified later on, it can effortlessly be expanded to the previous stage.

4 Synergistic modeling and simulation using SDL

As the SD approach comprises both the decision-making level and the functional area of a company, this approach offers a formal basis for the synergistic modeling and simulation within a domain. Consequently, the consistent development of a company-specific SDL leads to numerous possibilities of analysis (figure 2). With the help of already available reference models adapted to the individual processes, activities and data of a company within a necessary customizing process, the division managers, e.g., of functional areas, are put in the position to analyze their area of responsibility in due consideration of several other levels of decision-making in the company. The inclusion of SDL units from more than only one functional or decision-making level can lead to a) the development of more informed decisions and choices, which consider interests of other decision-makers in the company, b) new insights, which can illustrate the previously unknown far-reaching scale of an evaluated decision, c) the detection of potential conflicts which can be counteracted in advance and d) the development of argumentation to convince individuals

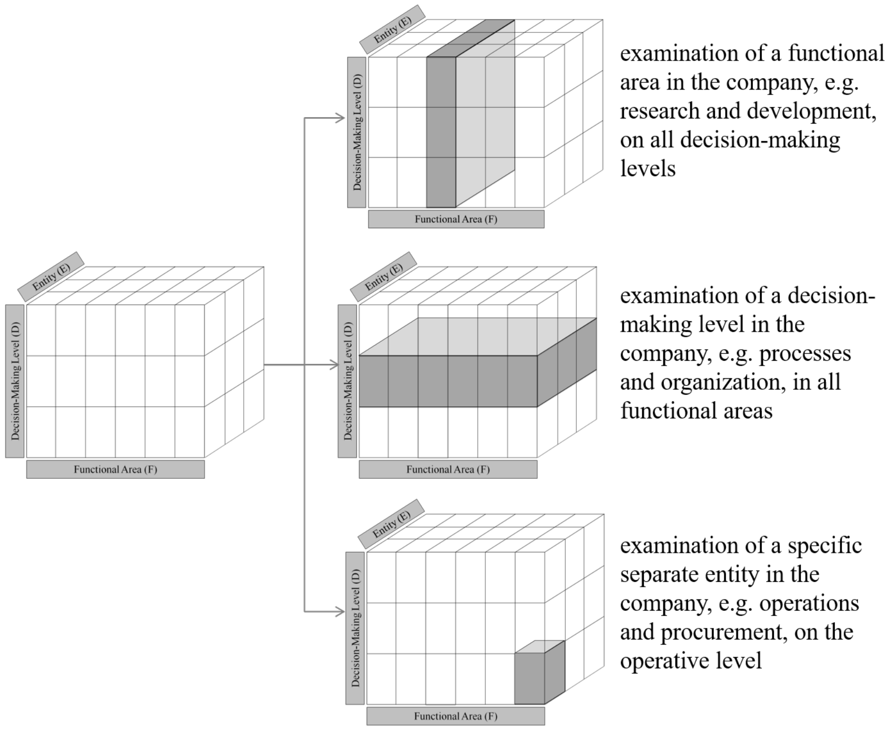

Figure 2: Possibilities of analysis with the SDL approach

both in the own functional area but also from other involved decision-making levels that the targeted decision is sensible and appropriate. However, these exemplary possibilities of application depend on an SDL which is properly maintained by all departments in the company.

In addition to the possibilities mentioned above, such a synergistic modeling approach will lead to further substantial benefits. A model is only valid until the gained hypotheses and insights are disproven on empirical basis. This means that the gained results do not necessarily have to be true, whether due to analytical, formal or fact-based logic relationships. Both the units deemed relevant for the model and the links among these are subject to assumptions of at least one individual. Therefore it is true for such models as well, that wrong premises like units and/or erroneous deductions in form of links between the units may imply wrong conclusions. Strictly spoken, a model can only be accepted as true after it was definitely verified. Usually this would suggest an empirical study in form of a long-term observation of real relationships and behaviors, the results of which can be juxtaposed to the results of the simulation afterwards (further details regarding these aspects are discussed in Karl 2014).

This point shows the decisive advantage of the synergistic modeling approach with which the model designer will be able to build a feasible link between simulation and the study of decision making. If, ideally, a decision making game has been established in parallel to the simulation and is based on the identical model (e.g. developed out of an SDL), the "time lapse" function of the game can help to form an empirical basis from the behaviors and decisions of the participants. A thorough analysis of the decisions made in the game forms an empirical basis to assist in a first verification resp. falsification of the model. Hence, a falsification based on these premises can help to improve the quality of the simulation model as a whole but without the need to monitor the whole period of observation in real time. Based on this approach, the first step to develop SDL units is the localization of relevant entities, which need to be formally and explicitly described according to the specific aim of the model. This description is achieved

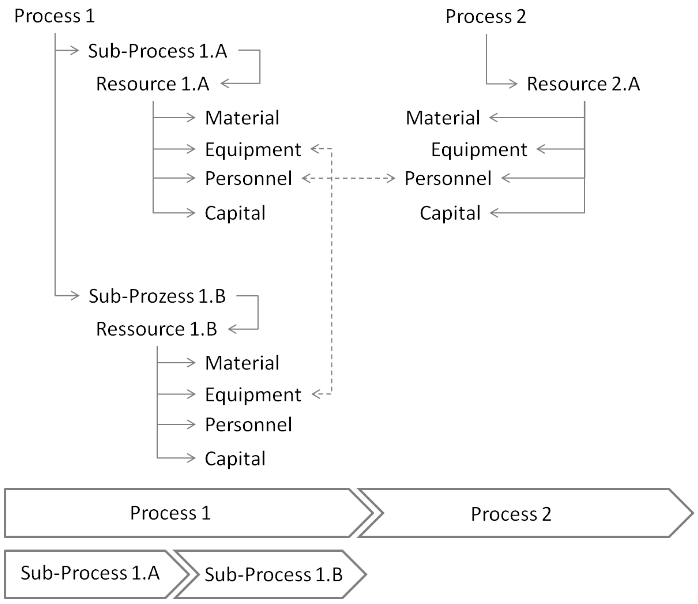

Figure 3: SDL Process Ontology

with the SDL process ontology, devised specifically for such purpose and described in the following.

5 SDL Process Ontology

Each entity of the SDL is structured in itself in a specifically laid-out process ontology (PO). The term ontology (the study and categories of being) originates from philosophy but is, in computer sciences, frequently seen as a clearly separated and formally structured description and illustration of terms, components etc. and their relation to each other in a given area of interest. Such ontologies are often employed for the organized exchange of knowledge (e.g. knowledge representation in the section of artificial intelligence). In contrast to taxonomies, which only display a hierarchical sub-categorization only, ontologies are in the position to depict relationships between the individual terms. For further details, please refer to, Uschold & Grüninger 1996, Oberle et al. 2009, among others.. In the first stage, the SDL PO lists the resources included in a specific process. These are subdivided in, e.g., material, tools (e.g. equipment or machinery), personnel and capital as well as the dependencies between the individual resources (figure 3).

This means that atoms, for instance, can be allocated to the monitored resources. These resources contain the properties allotted to the atoms which, in turn, results in a dependency on the according functional areas. The second stage SDL PO integrates the previously defined objects of the first stage within a larger context and therefore creates a relationship between the individual processes. As a consequence, the previously introduced molecules consider the resources and properties of the atoms in a larger scale and allow the illustration of processes. These represent cost- and production-oriented activities and are summarized as process chains in the components. Hence, the application of a PO predefines the first inner structure of a domain-specific SDL, thereby allowing model developers to quickly locate the required elements for the respective model purpose and include them in their individual models. On the basis of the SDL PO, first formally distinct and transferable networks of processes, objects and interdependencies are designed and can be drafted in more detail with the help of a specific SDL notation.

6 SDL notation

Fundamentally important for the systematic expansion of an already developed SDL, an according notation is as elementary as the structured basis supplied by the PO. The notation aims at the possibility to establish SDL as database-supported libraries in the long term. This notation accounts especially for the formal predicate logic. To facilitate the denominations, each entity is assigned a unique identification number (uid) within its own field. With the assistance of further attached uids, the development respectively the affiliation of an entity within a group can be understood in the future. The separate units are defined as follows:

Atom:

$$a_{R,,uidn.\ldots uidm} := a\left(D, p, F(p)\right) \in f(p)\ [u(p)] \tag{1}$$

Molecule:

$$m_{P,uidn.\ldots uidm} := m\left(D, F(p), \sum_{k}\left(a_k\right), \sum_{l}\left(m_l\right)\right) \in f(p)\ [u(p)] \tag{2}$$

Component:

$$c_{P,uidn.\ldots uidm} := c\left(D, \sum_{j}\left(Fp_j\right), \sum_{k}\left(a_k\right), \sum_{l}\left(m_l\right), \sum_{m}\left(c_m\right)\right) \in f(p)\ [\sum_{j}\left(up_j\right)] \tag{3}$$

mit:

D = decision-making level $\in [CMD, CCD, CPD]$;

p = predicate $\in [property\ 1, ..., property\ i]$ with i$\in \mathbb{N}$;

F(p) = function $\in [SO, RD, FG, MS, HL, OP]$;

f(p) = form $\in [stock, flow, const, var, system]$;

u(p) = unit $\in [SI - unit, currency - unit, ...]$;

R = resource $\in [MA = material, DE = device, WO = worker, CA = capital, ST = storage]$;

(In case an atom is used as auxiliary variable in the model, AUX = auxiliary is used)

P = process $\in [PL = planning, SF = site\,facilities, EA = earthworks, SC = shell\,construction]$;

uidn = unique identification number n $\in \mathbb{N}$;

uidm = unique identification number m $\in \mathbb{N}$;

k = uid of included atom;

l = uid of included molecule;

j = uid of included component;

It is necessary to keep in mind, that a predicate p can be a conglomerate of different properties, e.g. the resource material can contain a quality, a weight and a price (arity of three). Hence, if an atom consists of a predicate with an arity of x and is subject to an itemization process in modeling, it needs to be broken down to further independent atoms with an arity of one to allow its use in the following simulation. Within a simulation, an atom is always required to be downgraded until it describes only one property. Three modeling cases can be distinguished in general (figure 4). In the first case, the bottom-up method (abstraction in increments following VDI 3633 (1996)) helps to form a molecule out of three already existing atoms. Here, two atoms influence the third one (e.g. var + const → var, var + const → flow, var + const → stock). The second case presupposes the existence of at least two more atoms, of whose coaction a previously unknown third atom is created. This means that one further atom was created during the construction of a molecule. The third case represents a recursive form, in which the implementation of the top-down-method (itemization in increments following VDI 3633 (1996)) transforms an existing atom into a molecule. For this, possible influences on the atom were identified. The result of this observation is the creation of more atoms.

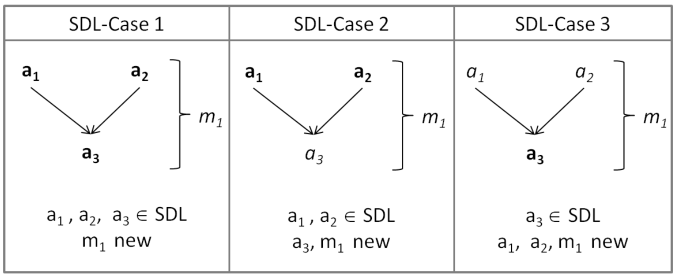

Figure 4: SDL model cases

As models on the basis of an SDL can be of substantial size and complexity – depending on the problem setting and the desired insights – a unified graphic mode of representation is introduced in the following. It can be used to facilitate the observer's understanding of complex models and elucidate the main features of an SDL-based model.

Part III

Exemplary development of a model library

Apart from the concept of a domain-specific SDL, which is based on the SD approach and called construction dynamic library (CDL, figure 5), a cadre of module-oriented models will be introduced. Within the CDL, three significant areas are in the central focus: (1) the construction project: Construction Project Dynamics (CPD) (2) the construction company: Construction Company Dynamics (CCD) and (3) the construction market: Construction Market Dynamics (CMD). The CDL is supposed to enable users to depict both the construction industry and all involved parties in a network of linked operational, economic and market-dynamic processes.

These models and the included units are to offer the basis for further developments and should be summarized using the term construction dynamics (CD). The design of the different units will be shown in detail in the following to demonstrate the practical development of the CDL, taking the operative level (CPD) as an example. As the modeling of CD units is a recursive process, the development of the exemplary units is also intentionally illustrated in this form. As a consequence, the potentially missing atoms needed in part 12 on page 13 and the equally lacking units in part 13 on page 16, respectively, are going to be modeled within these parts. As the formal approach is analogue both on the tactical as well as the strategic level, an explicit illustration of the development process on these levels is deliberately

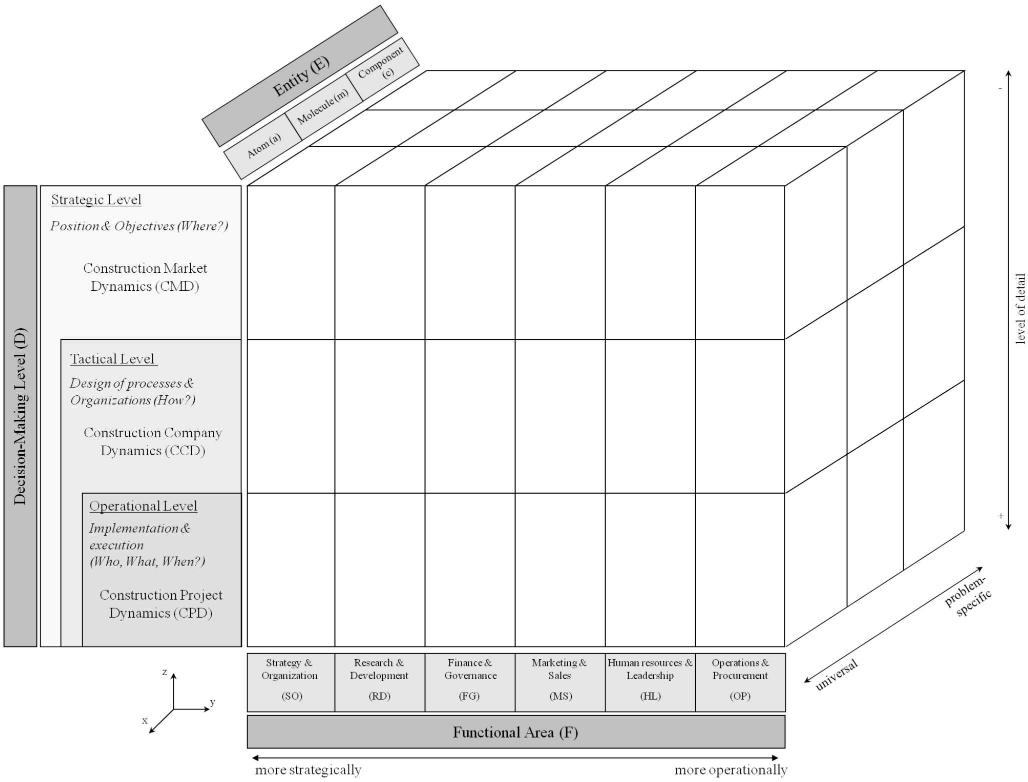

Figure 5: Structure of the CDL

omitted.

7 Purpose of the model

A project model is supposed to be generated on the operative level while applying the SDL approach. The aim is to have a project model which can display connections and dependencies or predict, both correctly and qualitatively, tendencies and dynamics of developments. These predictions should be formed on the basis of, e.g., risks in the construction operation itself, volatilities of labor or operating costs as well as the potential influence of experience and necessary on-the-job training required by the personnel of a construction site in a surface construction project. Additionally, elementary supply chains will be shown in the project model to allow examination of their influence on the project. Primarily intended orientation of the model *construction project* are the involved costs and the execution time.

8 System limits

Only surface construction is targeted in the model *construction project*. Furthermore, only the operations from the setup of the construction site to the completion of the building shell are considered in detail. These, in turn, are defined by the primary processes earthwork, reinforced concrete construction including formwork, reinforcements and concrete works, as well as brickwork. Resources like material, tools and personnel are included in the calculations. The remaining unconsidered tasks are seen as services contributed by subcontractors or third-parties.

Table 1: Examplary resources of construction site setup

process	material	equipment	personnel
construction site setup	-	crane	crane operator
construction site setup	-	personnel container	workers
construction site setup	-	construction management office	construction manager
construction site setup	-	sanitary facilities	all
...	...	...	...

9 Fundamental reference figures

First, the model *construction project* is conceptualized on the basis of the previously defined system limitations and then, in the following, qualitatively modeled in detail using the top-down-method (VDI 3633 1996). At this stage, the model *construction project* is built on fundamental reference figures and their relationships to each other. The reference figures needed later for the simulation can be acquired from real projects or from sources in literature (e.g. statistical databases for construction costs). A first project definition is determined with the following input parameters: a) gross volume (GV) , b) gross floor space (GFS), c) free ground area (FGA), d) areas of the exterior and interior walls (AEW and AIW). Additionally, the required overall resources are calculated with the help of the materials needed by each of the trades. For this, ratios are taken from previously published technical literature (e.g. Spranz 2003). Further input parameters are included: e) proportion of solids, f) proportion of formwork, g) proportion of reinforcements.

To determine the necessary amount of material to be excavated, the following parameters are considered: h) depth, i) additional excavation ratio. The parameter additional excavation ratio should give room for additional excavation work, which may be necessary depending on the depth and the resulting need to form berms. In the end, the output parameters of this model are quantities given for a) excavated earth, b) formwork, c) reinforced concrete, d) steel, e) brickwork (interior and exterior). Further parameters are relative auxiliary variables which may be useful in the later steps of the modeling process.

10 Identification of the relevant system parameters

The model *construction project* will be additionally specified in the due course of development under inclusion of the SDL PO (p. 7) and in line with the processes and upcoming tasks. In due consideration of the usual and conventional planning of preparations and operating procedures in the construction industry, a hypothetical and rough draft of a generic construction project will be introduced in the following. In this, the first project definitions of the underlying model are filled with more details. To prepare the following modeling of the units, indispensable information like, e.g., processes, resources and characteristics, defined by the SDL notation, is located with the help of the SDL PO (figure 6).

At the beginning of the actual production, the setup of the construction site requires attention. This part of the modeling is relevant because the construction site setup can have significant influence on the general expenses of the construction in the area finance and governance (FG). The choice of the individual elements of the construction site setup is based on Schach & Otto (2008) and is displayed in table 1.

After the setup of the construction site, the earthworks begin. These can usually be divided in the subsections of removal (excavation), hauling (transport) and disposal (Bauer 2007), whereas the first

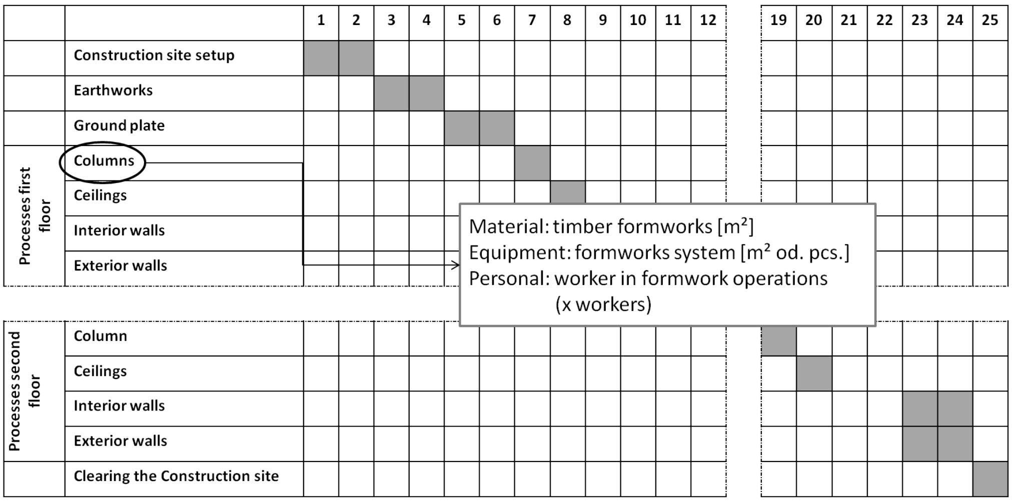

Figure 6: Rough operation chart of project model

Table 2: Resources earthworks

process	material	equipment	personnel
excavation	ground	excavator	operator excavator
transport	ground	truck	truck driver
...	...	...	...

two of these will be in the main focus of interest. The excavated earth is expected to be unloaded and disposed of without any further costs at the end of the transport. The equipment and the personnel is assigned accordingly (table 2).

The monitored construction of the building shell is segmented in the two phases concrete/reinforced concrete construction (ground plate and processes ground floor to second floor) and brickwork (only processes ground floor to second floor). The included process groups of concrete/reinforced concrete construction are formwork, reinforcing and placing of concrete (Bauer 2007). In this process a distinction is necessary between timber formwork (used, among other areas, in bridge construction) and system formwork (used, among other areas, in general surface construction) (table 3).

Based on the relevant system parameters which were identified in this phase, the key variables in the sense of the AMCA are elaborated in the following.

Table 3: Examplary resources building shell

process	material	equipment	personnel
formworks	timber	formworks system	worker in formwork operations
reinforcing	steel	-	worker in reinforcement operations
brickwork	bricks/ mortar	-	bricklayer
concrete pumping	concrete	concrete pump	operator of concrete pump
...	...	...	...

11 Atoms

In general, each single identified resource presents an atom with multiple attributes and can be formally described according to the SDL notation (for details refer to p. 8) as shown in the following. The atoms of some fundamental resources are listed in the following. These can serve as examples for the definition of further units.

concrete:

$$a_{MA,4} := a\left(CPD, p_{concrete}, F(p)\right) \in f(p)\ [u(p)] \tag{4}$$

$p_{concrete}(volume, spec.\ weight, spec.\ costs, ...)$;

F(p) $\in [FG, OP]$; f(p) $\in [stock, const, var]$;

u(p) $\in \left[m^3, to/m^3, to, Euro/m^3, m^3/t...\right]$, t = time unit

storage:

$$a_{ST,x} := a\left(CPD, p_{storage}, F(p)\right) \in f(p)\ [u(p)] \tag{5}$$

x $\in [material\ code]$

MA: 1 = soil, 2 = formwork, 3 = steel, 5 = brickwork (not storable 4 = concrete);

$p_{storage}\ (volume, area, material, costs, ...)$;

F(p) $\in [FG, OP]$; f(p) $\in [stock, const, var]$;

u(p) $\in \left[m^3, m^2, Euro/m^3, Euro/m^2...\right]$

concrete pump:

$$a_{DE,3} := a\left(CPD, p_{concrete\ pump}, F(p)\right) \in f(p)\ [u(p)] \tag{6}$$

$p_{concrete\ pump}\ (depreciation, interest, repair, fuel\ consumption, performance\ value, number, ...)$;

F(p) $\in [SO, FG, RD, OP]$; f(p) $\in [stock, const, var]$;

u(p) $\in \left[number, Euro, m^3, l/t, t/m^3, Euro/t, ...\right]$, t = time unit

concrete worker:

$$a_{WO,6} := a\left(CPD, p_{concrete\ worker}, F(p)\right) \in f(p)\ [u(p)] \tag{7}$$

$p_{concrete\ worker}(working\ time\ value, experience, motivation, spec.\ costs, number, ...)$

F(p) $\in [SO, FG, HL, OP]$; f(p) $\in [stock, const, var]$;

u(p) $\in \left[number, m^3/t, Euro/t, ...\right]$, t = time unit

The effect relationships between the individual atoms and their specific attributes are examined in more detail in the following. As a result, the previously defined atoms are combined and form molecules with their own system structure.

12 Molecules

Depending on the processes to be inspected, atoms are combined to form molecules. As the potential properties of atoms and, consequently, the resulting molecules are highly diverse, the following considerations are assigned to different functional areas. To set the structure of the molecules, a further discussion of the possible properties of the individual atoms is necessary. This specification is dependent on the purpose for which the molecule is to be developed. As an example, the modeling of the sub-process concreting as part of the building shell will be described in the following section.

12.1 Operations and procurement (OP)

The fundamental units of the sub-process concreting (figure 7 at p. 15) are illustrated in the following, further units in the sub-processes formworks, reinforcing and brickworks can be developed in the same way. To begin, again a basic molecule is devised and then described in detail. The index SC,3 stands for the third process of the building shell construction (SC = shell construction, 1 = formworks, 2 = reinforcing, 3 = concreting).

concreting:

$$m_{SC,3} := m\left(CPD, OP, a_{MA,4.1}, a_{DE,3.1}, a_{WO,3.1}, , a_{WO,6.1}\right) \in flow\ [m^3] \tag{8}$$

Similar to earthworks, one type of material and one piece of equipment are considered here ($a_{MA,4}$ und $a_{DE,3}$). Hence, the properties have the following details:

amount of concrete to be poured:

$$a_{MA,4.1} := a\left(CPD, amount\,of\,concrete, OP\right) \in stock\ [m^3] \tag{9}$$

performance value concrete pump:

$$a_{DE,3.1} := a\left(CPD, performance\,value\,concrete\,pump, OP\right) \in const\ [m^3/t] \tag{10}$$

with t = time unit

A difference, however, is the involvement of two different groups of personnel. The inclusion of a concrete pump requires an operator ($a_{WO,3}$) on the one hand and a concrete worker ($a_{WO,6}$) on the other hand. Regardless of the fact that the concrete pump represents the central and foremost piece of equipment in this process, it appears reasonable to define the performance of the concrete worker as the maximum performance of the pump is primarily limited by the capabilities of the employee using it. The modeler can decide himself or herself (during the design of the simulation) whether this aspect should exert any influence or not.

performance concrete worker:

$$a_{WO,6.1} := a\left(CPD, performance\,value, OP\right) \in const\ [m^3/t] \tag{11}$$

with t = time unit

Similar to earthworks, in the due course of concreting a time-dependent process of gaining experience through adjustment to the task may be anticipated. This effect of adjustment to work is considered as follows:

adjustment to work concrete worker:

$$a_{WO,6.2} := a\left(CPD, adjustment\,to\,work\,factor\,concrete\,worker, OP\right) \in var\ [-] \tag{12}$$

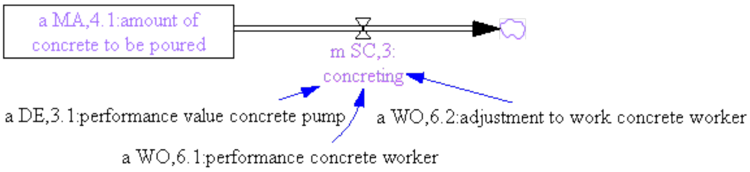

Figure 7: OP model concreting

12.2 Human resources and leadership (HL)

For the consideration of personnel-related aspects in the building shell process, the following units may be of interest, too (analog for the other trades):

Experience concrete worker:

$$a_{WO,6.3} := a\,(CPD, experience\, factor\, concrete\, worker, HL) \in const, var\ [-] \tag{13}$$

Motivation concrete worker:

$$a_{WO,6.4} := a\,(CPD, motivation\, factor\, concrete\, worker, HL) \in const, var\ [-] \tag{14}$$

Additionally, the number of employees per trade is especially important for the areas operations and procurement (OP) and finance and government (FG) (analog for the other groups of persons):

Number of concrete workers:

$$a_{WO,6.5} := a\,(CPD, number\, concrete\, workers, HL) \in const, var\ [qty.] \tag{15}$$

12.3 Finances and governance (FG)

The standard price contract is in the center of interest in the currently inspected operative area of the functional level finance and governance. This includes the separate costs of the following items of work: 1) labor costs, 2) costs of construction material and 3) equipment costs (Leimböck & Klaus 2007).

Like in the area of operations and procurement (p. 14), the main interest is the costs of the concreting process again. The units developed in this context can be modeled for the other trades following the same procedure. Taking into account the previously devised units for the calculation of the equipment costs in the area of earthworks, the equipment costs are determined for the concrete pump involved in the concreting process. Opposed to that, the costs of material and personnel need to be differentiated much more than before. To specify the expenses for the material, the price of concrete and the quantity of it to be deployed are taken into account.

price of concrete:

$$a_{MA,4.2} := a\,(CPD, spec.\, costs\, concrete, FG) \in const\ [Euro/m^3] \tag{16}$$

concrete costs:

$$m_{MA,4.1} := m\,(CPD, FG, a_{MA,4.1}, a_{MA,4.2}) \in const\ [Euro/t] \tag{17}$$

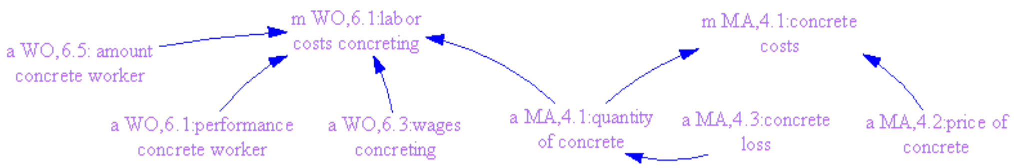

Figure 8: FG model concreting

with t = time unit

A possible and process-related concrete loss has to be considered and is included in an atom with a percentage factor of the overall quantity of concrete to be processed.

concrete loss:

$$a_{MA,4.3} := a\,(CPD, factor\,of\,concrete\,loss, FG) \in const\ [\%] \tag{18}$$

The atom $a_{MA,4.3}$ causes an increase of the needed quantity of concrete ($a_{MA,4.1}$), resulting in an increase of the construction material costs. Apart from the material costs, the personnel costs represent another part of the overall expenses. Therefore, the labor costs for this process are modeled in relation to the amount of concrete to be deployed $a_{MA,4.1}$, the performance value of the personnel $a_{WO,6.1}$, the number of the assigned employees $a_{WO,6.5}$ and their pay $a_{WO,6.3}$ (figure 7).

labor costs concreting:

$$m_{WO,6.1} := m\,(CPD, FG, a_{MA,4.1}, a_{WO,6.1}, a_{WO,6.3}) \in const\ [Euro] \tag{19}$$

wages concreting:

$$a_{WO,6.3} := a\,(CPD, spec.\,wages\,concrete, FG) \in const\ [Euro/t] \tag{20}$$

with t = time unit

13 Components

This phase of the modeling is characterized by the linking of molecules and atoms to form components which have their own internal problem-related processing logic. Building up on the already modeled units, these components depict a) the construction site setup, b) the earthworks and finally c) the process of the building shell construction. The latter will be described in the following as an example.

13.1 Costs building shell

Based on the general project model (compare 6 on p. 12) and apart the already discussed processes, the component *costs building shell* ($c_{SC,5}$) incorporates the sub-processes formworks ($c_{SC,1}$), reinforcing ($c_{SC,2}$), concreting ($c_{SC,3}$) and brickworks ($c_{SC,4}$). A distinction is necessary in $c_{SC,1}$ between timber formworks ($c_{SC,1.1}$) and system formworks ($c_{SC,1.2}$) which will be considered in the subsequent modeling process. For this aim, an individual component will be modeled for each sub-process, all of which can finally be found in the component costs building shell.

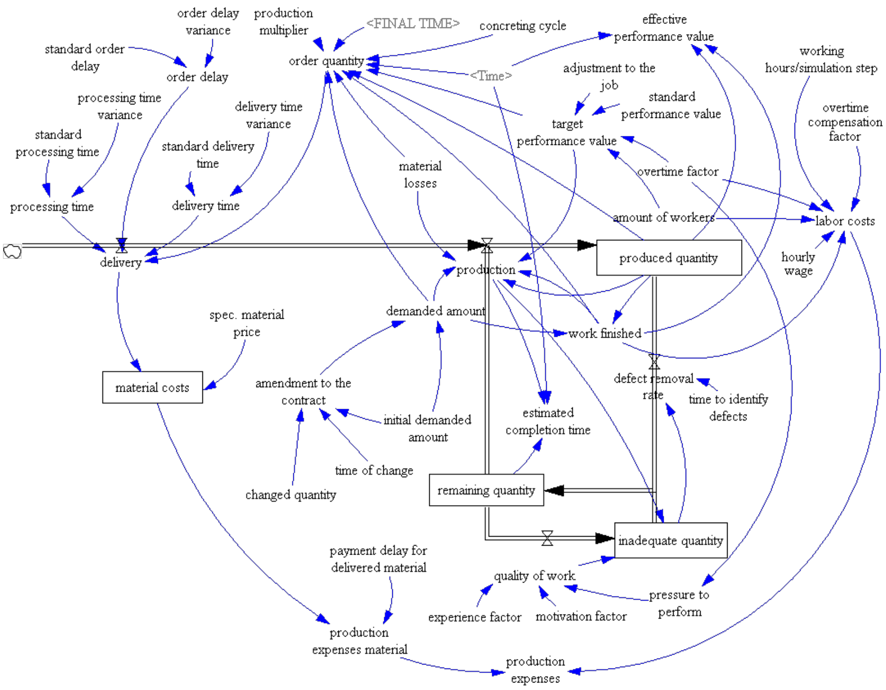

Figure 9: Component concreting

$$c_{SC,5}: \quad = \quad c(CPD, FG, c_{SC,1}, c_{SC,2}, c_{SC,3}, c_{SC,4}, \left\{ \begin{array}{c} c_{EA,1} \\ c_{EA,2} \end{array} \right\}, \left\{ \begin{array}{c} c_{SC,1.1} \\ c_{SC,1.2} \end{array} \right\}) \in stock\ [Euro] \tag{21}$$

Concreting

As a preparational step, a standard component is devised to serve as a basis for the modeling of the above-mentioned components. Afterwards, components for different trades where developed on basis of the standard component. In general, two possibilities are available if a standard component has already been developed and is in use: a) irrelevant units are assigned the value zero if the system permits or b) the irrelevant units are removed completely from the component and the connections are adapted to fit the new system purpose. Even if a standard component is employed, the consistency and reliability of the derived components has to be tested and confirmed in both cases. Figure 9 shows the second alternative, in which irrelevant units and connections have been removed and other necessary units were integrated in the concreting component ($c_{SC,3}$). All other components are developed in the same manner based on the standard component.

Part IV

Implementation of the model elements

The practical testing of the previously developed models in form of simulations is demonstrated in the following for the operative level. Depending on the intended aims, a diversity of concepts can be realized with the help of the already developed CDL units or their subsequently generated models (part III, p. 9 ff.).

14 Structure of the project simulation

Previously, the individual units were qualitatively viewed and registered. To prepare a quantitative examination and the subsequent analysis, the hitherto developed project model concept is implemented in Vensim. The simulation does not serve the primary aim to offer a complete, comprehensive and practicable method for the generation of cost-relevant data being as precise as possible. The main focus is rather to draft a realistic project model, which allows elucidating the relationships on the one hand and the influences on the other hand – from a qualitative or a relative and quantitative perspective. In addition to that, the simulation serves as a validation of the model and should help to determine realistic parameters.

As Vensim has already been used since the modeling phase, the contained project model needs to be equipped with corresponding mathematical equations as well as realistic input data in the current simulation phase (The project model consists of more than 750 differential equations). The validation phase comprised both checks executed with a spreadsheet program or as manual calculations, aiming to verify the general validity of the model and also the system stability and integrity. In the following the developed central graphical user interface (GUI) is introduced. Additional views in Vensim allow the input of project definitions as well as simulation constants. The design of the simulation resulted in the *Construction Project Flight Simulator* (CPFS) of which the GUI is shown in figure 10 on 19.

The previously developed CDL units are assigned to 24 views in the CPFS, where the different parameters, e.g., basic settings of the simulation, learning ratios, operating expenses and performance values can be adjusted in detail. An upgrade of the introduced basic project model (refer to p. **??**) appeared necessary and was implemented into the CPFS. The resulting project definition is shown in figure 11 on 19.

Main difference to the basic model is the extended degree of detail in regard to the materials required by the project, especially dependent on the dimensions of the project as a whole. Due to this, further units are to be included in correspondence to the previously described boundary conditions of the project model (refer to p.**??**). These units can represent specific dimensions of the ground plate, the ceilings or the columns, for example. To achieve a higher flexibility of the CPFS, the input of a prop grid is possible. Based on these additional inputs, all further required data is generated by the model, e.g. volume and areas for the formworks. According to the previously defined boundary conditions, the project model or the according simulation should be able to depict buildings of up to 10 storeys. Thus, the introduction of building floors as a definition is strictly necessary, too.

Part V

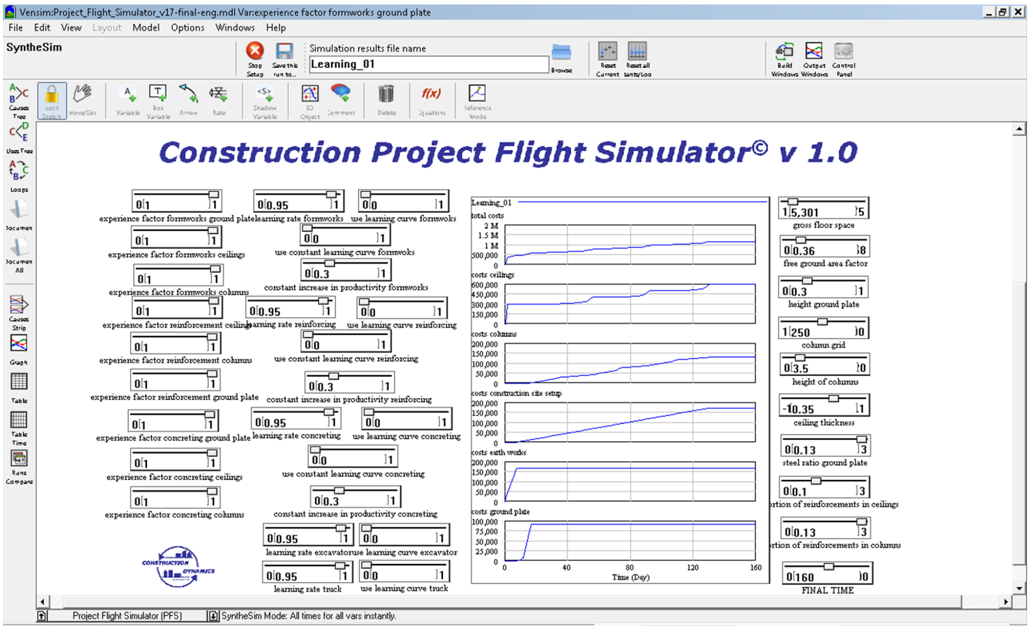

Figure 10: CPFS user interface in Vensim

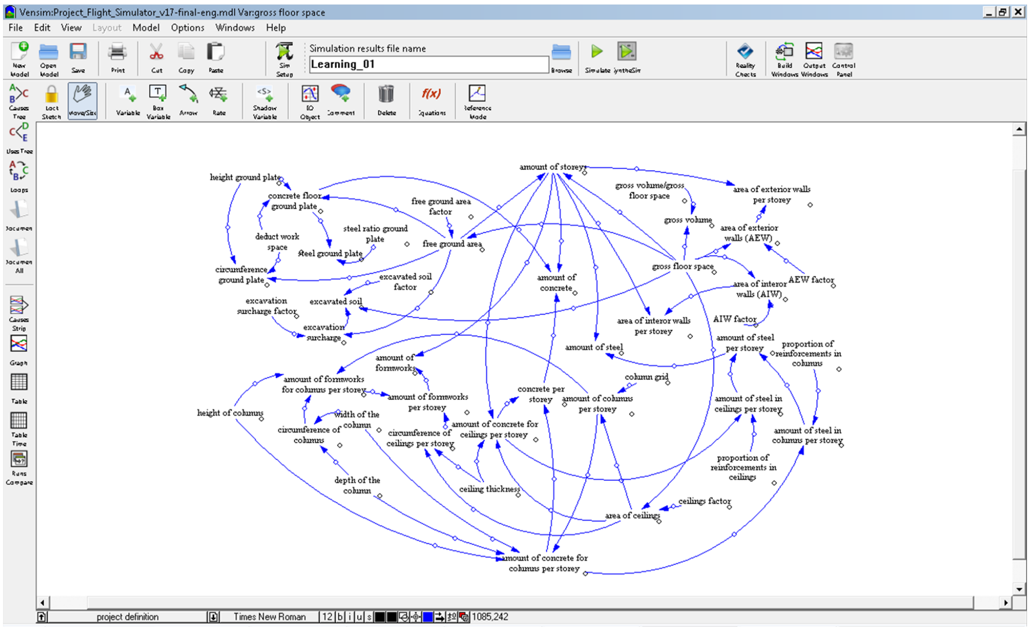

Figure 11: Project definition of the CPFS

Selected results of prototypical implementation

Based on the simulation devised in part 14, exemplary results of the implemented simulation experiments are introduced and discussed in the following.

The quantitative analyses executed with the following simulation studies serve the verification and validation of the simulation models on the one hand, but, on the other hand, the results should also offer indicators for the examination of specific situations and behaviors of the model and thereby potentially allow the derivation of decision dispositions. Especially the illustration of relationships and dependencies between the different elements should support the evaluation thereof and, even more so, the search for alternatives. Strong emphasis is placed on the overall costs and the duration of the project. A contractually fixed maximum duration for all processes of 160 days must not be exceeded.

Without any doubt, the devised simulation can be used to create and examine a diversity of scenarios. In the following five elemenatry scenarios will be introduces. In these scenarios, the system reactions on changes of the input values are explicitly fixed and are executed as deterministic simulations once only. The question settings for the individual deterministic scenarios are the following:

- Scenario S1 - Basic: Ideal construction operation, all further scenarios are compared to S1.
- Scenario S2 – Vocational adjustment: Which influence do familiarization effects have on the work? This scenario could answer the question if it is worth to consider vocational adjustment within the planning and execution of a construction project.
- Scenario S3 - Experience: Which influence can be measured in case of a less experienced workforce? This aspect could be important especially for projects with a high amount of subcontractors (like in global projects). In such cases it is necessary to know a) which performance can be assumed compared to the own work force and b) is it worth to invest in education for foreign work force?
- Scenario S4 - Overtime: What is the influence of overtime? This scenario might give hints to decide until which limit mandated overtime can be seen as a common strategy to face delays within construction.
- Scenario S5 - Overtime (S4) & Vocational adjustment (S2): In how far does a combination of overtime and adjustment to the work result in the shortest possible period of time needed for the completion? Secondly, in how far can potentially negative effects of overtime be compensated by familiarization effects?

15 Simulation experiments

Scenario S1: Basis

The basic scenario S1 represents the ideal construction process. All material (except concrete) needed for the first production cycle is present in full quantity at the beginning of the construction. Consequently, no placing of orders is necessary at the start. All employees have maximal experience and motivation, i.e. the work can be done with optimized quality and no revisions of previous processes have to be carried out. Furthermore, losses due to storage handling or wear and tear of the material are excluded. Theoretically possible increases of production due to familiarization to the job are not considered in S1 and no overtime is possible. Both the overall project costs and the overall duration for the regarded processes are basis for the comparison to other scenarios.

Scenario S2: Vocational adjustment

In S2, learning curves are defined for each work process (formworks, reinforcing, concreting) and serve as basis for the examination of effects which the work adjustment can exert on the overall costs and duration. The learning rate is set to 95% and develops individually for each process from the first activity and then continuously during the whole construction process. The maximal realizable increase of productivity is +30%. Results: costs -2,79%, time -8,40%.

Scenario S3: Experience

Scenario S3 focuses the influence of less experienced workers. In this case the work experience of the employees is assumed to be 10 % less than the given standard, resulting in a decrease of the same amount in the execution of assigned tasks. In contrast to S2, the reduction does not exert direct influence on the performance value, but mainly on the quality of the work results. Thus, the lower experience level leads to a faulty workmanship and then to the necessity of revision and corrective activities. Here, the time required for the detection of substandard work results is set to one day, i.e. potentially occurring defective results can be identified and corrected by the construction management on short notice. Result: costs +4,60%, time +10,00%.

Scenario S4: Overtime

Inspecting the scenario S3, the influence of mandated overtime on the overall project costs and on the overall completion time appears of central interest. To gain insights here, the available working hours per day are increased by 20 %. Assuming that the quality of work remains the same in spite of the mandated overtime, i.e. the overtime does not lead to substandard quality of workmanship, the scenario S4.1 displays the following result: costs -1,39%, time -10,69%. If the directive of overtime is linked to the productivity and quality of workmanship (Ibbs & Vaughn 2015), i.e. the overtime has a detrimental effect on the quality of the work and thereby causes the need of revision and repair cycles, the result of scenario S4.2 is this: costs +2,88%, time -2,29%. Just as in scenario S3, S4.2 also expects the time required for the detection of substandard work results to be one day.

Scenario S5: Overtime (S4) & Vocational adjustment (S2)

Scenario 5.1 is supposed to represent a good case scenario, combining overtime (S4.1) and vocational adjustment (S2). This scenario, compared to the basic scenario S1, results in the following changes: costs -1,39% and time -11,45%. S5.2 poses the question in how far the negative influences of mandated overtime in scenario 4.2 can be balanced with the consideration of vocational adjustment effects. The results of scenario 5.2 in comparison to the basis scenario S1: costs +2,44%, time -3,05% and comparing scenario S5.2 to S4.2: costs -0,40%, time -0,78%.

16 Discussion of the simulation experiments

The contractually set completion time of 160 days is undercut by 18,12% in the basic scenario S1. This means that in further scenarios a potential time delay would be tolerable up to this percentage – independently of the incurred costs. Based on the basic scenario S1, the scenario S2 with the inclusion of vocational adjustment effects leads to a reduction of the overall project costs of nearly three precent and saved time of more than eight percent (figure 12).

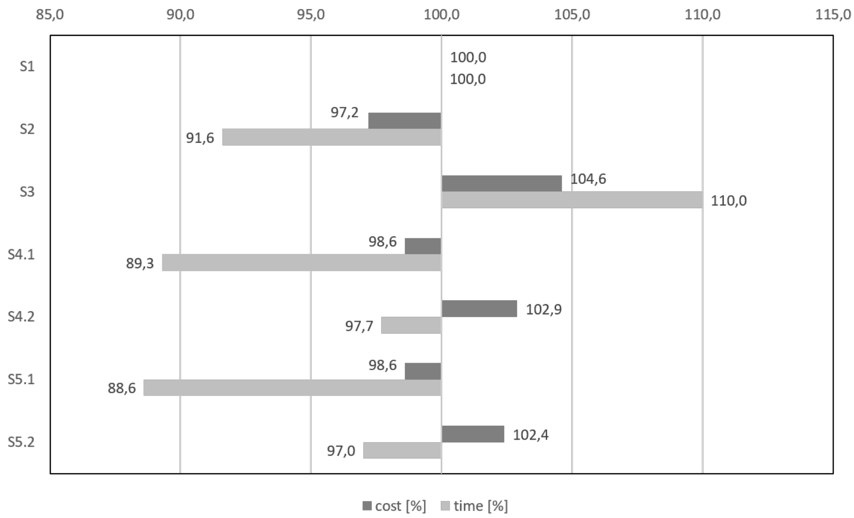

Figure 12: Simulation results

It is questionable, however, in how far such effects of adjustment to the work can be initiated and operatively maintained for extended periods of time. Therefore, the result of S2 demonstrates the theoretical cost-saving potential of vocational adjustment effects, but further research is required in this field to certify how realistic these effects are. In contrast to S2, scenario S3 considers a reduced experience of the construction site personnel and its effect on the quality of realized workmanship. A reduction of 10% results in additional overall project costs of almost five percent and additional time requirements of 10%. The increase of costs as well as needed time fulfilled the expectations. The fact that the percentage of the additionally needed time precisely matched the percentage of reduced experience in this scenario is a coincidence which can be proven by variations with other reductions of experience. A mandated overtime of 20% leads to the reduction of overall costs of more than one percent in scenario S4.1. Especially apparent is the saved time in this scenario, at almost 11% a substantially higher value than in scenario 3 including the factor of work adjustment. Following the assumption that mandated overtime has a negative impact on the quality of work, scenario S4.2 displays an increase of the overall project costs of nearly three percent. Despite the necessary cycles of revision and repair, project duration shrank by more than two percent. This means that the influence on the quality of workmanship caused additional costs due to the cycles of revision and repair, but nevertheless the overtime still affected project duration in a positive manner. Especially in these scenarios, a valid determination of both increases and decreases in costs or required time is substantially difficult, as a reliable statement would need more detailed input data for the illustration of the relationship between overtime and work quality. The missing input data could be obtained from additional field studies. Despite that, the developed simulation model appears to depict the effects of the different scenarios correctly and can, therefore, demonstrate the relationships at least qualitatively. The scenario S5.1, originally seen as good case and supposed to show the advantages of combining overtime (S4.1) and adjustment to the work (S2), demonstrated a reduction of project costs indeed and a decrease of project time of almost 12% in comparison to the basic scenario S1. However, when compared to the overtime scenario S4.1, the inclusion of work adjustment effects has only marginal impact on the final values. The reason for this is the availability of the required material. While the materials and resources necessary for the implementation of the first production cycle are available in sufficient quantity at the start of the scenarios S1, S3 and S4.1, the situation which develops in S5.1 does not allow the crew to deploy their full performance potential. Although the increased frequency of order placement allows the execution of work processes, but the storage capacity limited to a specific value does not provide enough room for an increased stockpiling. This, in turn, leads to a production process which is not running smoothly and in the best way. Even though a theoretically higher production performance is available, this is only applicable up to a certain limit. Thus the expected advantages cannot be realized in scenario S5.1, because the production performance is constricted by the storage situation. The scenario S5.1 demonstrates that no more than 12% of time can be saved under the given circumstances. If the stockpiling is adapted accordingly, scenario S5.1 can realize a theoretical time saving of up to 41%. Scenario S5.2 shows that the negative effects of mandated overtime in scenario 4.2 can be countered marginally only with the inclusion of vocational adjustment effects. Compared to the basic scenario S1, S5.2 results in a cost increase of more than two percent. The overall project duration can be reduced by approximately three percent. In addition to that, the results derived from the S5 scenarios highlight the fact that due to diverse interdependencies and feedback effects within the system, a superposition of results from different scenarios (e.g. S4+S2) is not directly possible. Even though the projects can be completed within the set time limit in the discussed scenarios and a (in German literature communicated) typical risk- and profit markup of between 1%-4% (Künstner et al. 2002, Hoffmann 2006) is assumed, a significant loss occurred in some of the projects. While not each project of a corporation is completed negatively and therefore the more successful projects balance the less successful ventures, the previous scenarios suggest that the usual risk- and profit markups appear to be insufficient and need to be reconsidered.

Part VI

Summary and outlook

The aim was to introduce the development and practical testing of a module-oriented modeling approach, which can be used in the simulation of multi-causal and dynamic relationships on different levels of an industry. The conceptual design of such a development framework for domain-specific system dynamic libraries (SDL approach) demonstrated that it is quite reasonable and possible to support the development of simulation models in that manner. This approach can be employed in an infinite number of applications. One example is the investigation of changes and their consequences within a project. Alternatively, this approach enables analyzing projects after completion to discover what and why happened in detail. Based on this, strategies can be formulated that, e.g. ensure that fabrication and construction proceed while changes are being resolved (Ibbs & Backes 1994). The findings within the prototypical implementation can be used as indicative of general trends. Every industry, every project is different, so slavish reliance on theses data is not warranted.

In the future, multidisciplinary R&D teams of practitioners and scientists from different domains have numerous possibilities to develop SDL units from varying perspectives. Especially in the construction industry, the approach introduced here can provide a valuable contribution to promote further developments. Beyond the formal procedure for the design of an SDL simulation, the first foundation of a domain-specific SDL (CDL) could be placed in the field of simulation.

Furthermore, CDL units, especially those serving the illustration of risks in different areas of the industry, could offer the basis for the development of special risk or danger models which can assist in the investigation of specific situations or behaviors and later the configuration of precaution and safety measures. As explicitly different levels and functional areas of a company are considered, an application in the research of organizational psychology would be possible, too. The SDL approach and the contained units could support the generation of hierarchically structured models through different levels and areas. Hence, interaction between the different levels (single individuals, teams or other functional units) could be interlaced and examined under consideration of further methods like the multi-level analysis (MLA, refer to Ditton 1998, Raudenbush & Bryk 2002, Langer 2009, Hox 2010.). This means that SDL units and the resulting models can generally be examined with other simulation methods, too.

Finally, it might make sense to include the SDL approach into simulation software products as a kind of (online supported) database, from which users can a) select suitable entities for their own model and b) upload entities to share with other model develpers. This would speed up the modeling and spread the SD method even further. Best way would be an open online database.

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