Mistakes in System Dynamics Models: An Educational Issues from the Systems Engineering Perspective

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Abstract

Systems engineering and development of system dynamics models are strongly interconnected. During this process of system construction, system dynamics modelling represents a useful approach to simulation of system behaviour over time and to support the quality and suitability of related decision. Appropriate application of systems thinking during the whole modelling process plays a crucial role and it is both problematic and challenging. This paper focuses on the identification of the issues occurring during the modelling process. The applied methods incorporates the experimental set-up, direct observation of modellers and qualitative analysis of developed models. Consequently, the list of identified drawbacks linked with particular systems thinking track is developed. The identified mistakes together with their linkage with type of thinking are summarised in a useful overview of what could and should be omitted or eliminated during the system dynamics modelling. Results reveal that operational thinking represents the most challenging thinking track. It is followed by non-linear, analytical, critical and structural thinking. Based on the achieved results, the modellers could analyse and revise their approaches and thinking patterns. These can be reconsidered and appropriately adapted following the principles of the correct application of systems thinking during system dynamics modelling.

Keywords
Systems engineering, System dynamics, System thinking, Modelling process, Thinking tracks

1. Introduction

Systems engineering and system dynamics represent disciplines that are strongly dependent on successful application of systems approach and systems thinking. Systems approach is the result of a scientific and technical way of thinking which complements reductionism, mechanism and analytical explanation embodied in the mechanistic approach. Due to introduction of system engineering–related breakthrough technologies such as computers, hydrogen bombs and space ships, large-scale problems began to penetrate our society. Consequently, as developed and maintained systems had been becoming more complex, the traffic-system breakdowns, environmental disasters and nuclear threats were immediately highly discussed. The society faced mutually interacting problems varying from technical and organisational to political, environmental and social ones. Moreover, the accelerating rate of change has joined the primary sources of issues. All of a sudden, it appeared that two hundred years of success from the classical science and technology perspective had created a form of development with embodied potential to devastate humanity. Gerald Weinberg states in one of his books that science and engineering have been unable to keep pace with the second order effects produced by their first order victories (adopted from Skytner (2005)).

Systems engineering represents a discipline that deals with radical improvement or design, modelling and development of complex man-made or artificial systems. Its fundamental task is to design and implement components that are heterogeneous and might comprise socio-technical subsystems. That is why a plethora of modelling tools, techniques or paradigms is applied in practice ranging from agile-related methods (Douglas 2016) and modelling languages (Combemale et al. 2017; Dori 2016) to specific modelling approaches such as agent-based or system dynamics modelling (Tučník and Bureš 2014). System dynamics is widely used when purely technical models and their simulations are hard to achieve. Nevertheless, development of appropriate, meaningful and suitable models with potential to support decision-making is not a trivial task. Therefore, application of systems thinking is a must of all systems engineers. Systems thinking is a point of view that helps system engineers to understand the complexity of the world and helps them understand the relationships among entities rather than the entities themselves (Akhtar et al. 2018). At the most general level systems thinking is considered as an approach, tool, methodology, or paradigm. Systems thinking has its fundaments in cognitive processes. Investigators have identified a wide variety of biases and mistakes in people's observations of data. Moreover, the judgments and interpretations based on these data are also associated with drawbacks (Doyle 1997). Nevertheless, variables such as attitudes, mental models, scripts, and schemes represent an integral part of systems thinking. Their mutual relationship is often complex and counterintuitive. Moreover, various studies published several decades ago confirmed that systems thinking is strongly influenced by the particular situation or context in which it is employed. That is why it is difficult to generalise results across domains and topics (Payne et al. 1992). Moreover, as Fisher (2011) pointed out, everybody is thinking differently. This statement can be applied to systems engineers as well. Despite these issues there is a progress of systems thinking development evidenced by various authors. Even more than two decades ago, Jackson (1994) described how advancements in disciplines such as soft systems methodology, soft cybernetics, or operational research support the concept of systems thinking and its spread among practitioners, researchers or academicians. The list of disciplines also included system dynamics as a modelling approach that enables capturing sytems thinking-related concepts like feedback, archetypes, accumulation, non-linearity, or behaviour.

Systems thinking contains a wide range of constructs and concepts such as complex adaptive systems, systems dynamics, or cybernetics, to name a few (Russel et al. 2014).This paper deals with the application of systems thinking in the process of system dynamics modelling as a tool for successful decision making. Although fundamental research studies deal with mutual connection of systems thinking, system dynamics and decision making (Doyle 1997; Sweeny and Sterman 2000), there is a research gap in the literature on empirical evidence how failures in application of systems thinking can negatively influence quality of system dynamics models and simulations and consequently degrade efforts in single systems engineering phases. Maani and Maharaj (2004) state that systems thinking leads to improved decision making and thus to superior performance is rather simplistic. They conclude that the degree of systems thinking does not play a significant role as certain types of systems thinking from the Richmond's classification (Richmond 1993) may be more substantial to superior performance. Nevertheless, the application of systems thinking is mostly associated with specific tools in practice. Visualisation of mental models, conceptual maps, decision trees, or class diagrams or activity diagrams can be exemplified. That is why this study follows up Maani and Mahraj's conclusions and tries to identify which thinking tracks are crucial for development of useful system dynamics models. The main objective of this paper is to present results acquired from an experiment focused on identification of failures in system dynamics modelling. The intention is to link existing problems with insufficient application of systems thinking in practice.

The remainder of this paper is structured as follows. This introductory section is followed by presentation of theoretical background of systems thinking and system dynamics. Next section deals with presentation of methodology applied. Acquired results are consequently presented and discussed. The last section concludes the paper.

2. Theoretical Background

The core concepts of systems thinking such as interconnectedness, feedbacks, adaptive capacity/resilience, self-organization and emergence (Williams et al. 2017) are applied in system dynamics with the intention to help people make better decisions when confronted with complex, dynamic systems (Schoenenberger et al 2018). The field provides a philosophy and tools to model and analyze dynamic systems. Equally important, the field provides techniques and tools to investigate current decision making and to help decision makers to learn. In comparison to differential and difference equations traditionally used for the representation of dynamic systems, the modelling language of systems dynamic is intuitive and it is common for all kinds of applications such as medicine, economics, management etc. This makes system dynamics an ideal tool for interdisciplinary work, and it makes learning more efficient because basic system structures tend to repeat themselves from one field of application to another.

There are two types of diagrams used in system dynamics. While causal-loop diagrams are used for qualitative modelling, stock-and-flow diagrams are applied in quantitative modelling that lead to models that can be consequently simulated and analysed. Details related to notations of both diagrams, their components, applied logic and both strong and weak points can be found in relevant literature (Richardson 1997; Lane 2000).

There is a strong belief that systems thinking can help us to tame the increasing complexity of our lifes (Maani and Maharaj 2004). Various studies focused on strong and weak points of systems thinking have been already published indicating that this expectation is legitimate but not easy to achieve. Systems thinking was already successfully applied in a plethora of domains ranging from soft disciplines such as ambient intelligence (Bureš 2006), business and economy (Vargo et al. 2017; Valention et al. 2015) and biological fields of study related to the environmental issues (Anandhi 2017) and/or infection prevention (Chuang et al. 2015); to technical disciplines such as information systems (Antonelli et al. 2013) or iron elements flow (Liu et al. 2014). Definition of systems thinking is quite difficult. The main issue is that understanding of systems thinking requires more or less application of systems thinking itself (Arnold and Wade 2015). Systems thinking is connected with various skills and capabilities. Palaima and Skaržauskiene (Plaima and Skarzauskiene (2010) state that in business settings dynamic thinking, system logic, interactivity, process orientation, understanding of mental models, or continuous learning represent the primary systems thinking capabilities. Richmond (1993) elaborates a set of systems thinking skills that have to be possessed by individuals to fully develop the impact and effectiveness of systems thinking. He emphasises that mastering systems thinking is based on operating on several thinking tracks at the same time. This task is quite challenging even with lower number of tracks or if the one is familiar with these ways of thinking. Therefore, the application of systems thinking can lead to cognitive overload in some cases. Nevertheless, it is possible to prevent people from becoming overloaded. One just need to a) explain people that they will have to operate on multiple thinking lanes simultaneously; b) explicitly describe what these lanes are; and c) suggest the progress based on mastering single thinking skills successively, only one skill at a time (Richmond 1993).

Various studies present thinking lanes in different context and extent. For instance, Maani and Maharaj (2004) reformulate Richmond's classification (1997), while Jackson (1994), Jokonya (2016) or Baghaei Lakeh and Ghaffarzadegan (2015) deal with one particular thinking skill. Needless to say, all these tracks of thinking are mutually interconnected. This study presents only those types of thinking that were proved to be relevant from a long time period. The following items on the list are applied in the result section of this paper. These thinking tracks are:

- Dynamic thinking,
- Generic thinking,
- Structural thinking,
- Operational thinking,
- Non-linear thinking,
- Continuum thinking,
- Scientific thinking,
- Critical thinking,
- Analytical/intuitive thinking.

Dynamic thinking represents the ability to identify and deduce behaviour patterns rather than focus on single events. It is thinking about phenomena as resulting from ongoing circular processes unfolding through time. Dynamic thinking skills are improved by having to trace out patterns of behaviour that change over time and by thinking through the underlying closed-loop processes that are cycling to produce particular events. Issues with dynamic thinking are very often demonstrated on the department store task (Baghaei Laken and Ghaffarzadegan 2015; Sterman 2002) or identification of systems archetypes can serve as an example of application of dynamics thinking in practice (Bureš and Racz, 2016).

Generic thinking is sometimes marked as an ability to view from 10 kilometres. Similarly to dynamic thinking, just as many people are captivated by events, they are generally locked into thinking in terms of specifics. View from 10 kilometres is a technique that stresses that our perception of a situation differs whether we are involved in a situation or whether we can have a look at a problem from a bird's eye view.

Structural thinking is one of the most disciplined of the systems thinking tracks. Within this type of thinking, people must think in terms of units of measure or dimensions. Physical conservation laws are rigorously adhered in this domain.

Operational thinking can be considered as a sibling of structural thinking. Thinking operationally means thinking in terms of how things really work rather than how they should work, theoretically work, or how one thinks it works. The difference between as-is and to-be is highlighted.

Non-linear thinking is closely associated with thinking in feedback loops and dynamic thinking as defined above. As already mentioned, when people keep closed loops in mind, they see the world as a set of ongoing, interdependent processes rather than as a laundry list of one-way relations between a group of factors and a phenomenon that these factors are causing.

Continuum thinking is supported primarily by working with simulation models that have been built using a continuous, as opposed to discrete, modelling approach. Discrete models are distinguished by containing many "if, then, else" type of equations.

Scientific thinking does not have to be connected merely with absolute numerical measurement. Scientific thinking has more to do with quantification than measurement. Thinking scientifically also means being rigorous about testing hypotheses. The hypothesis-testing process itself needs to be informed by scientific thinking. Hence, this track of thinking is closely related to structural thinking.

Critical thinking helps us to deal with information, analysing its source and thinking carefully about all related aspects and metadata. Critical thinking is very often associated with “fact checking”. In this way, it is connected with operational thinking as it helps to build more appropriate and accurate mental models which properly represent the reality. Not only information resources are scrutinised during application of critical thinking. The content of the system itself or its representation in a form of any type of model is called into question. The key question “Really?!” plays the crucial role in critical thinking.

Analytical/intuitive thinking is associated with the dual-process model. This model is grounded in a theory proposed by Schneider and Shiffrin (1977). This theory for information processing comprises two primary modes of cognition: controlled search and automatic detection. Based on these two modes, Kahneman and Frederick (2002) established a concept of cognitive process marked as System 1 and System 2. While System 1 is associated with intuitive thinking, System 2 applies analytical thinking. While System 1 procedures are automatic and effortless, System 2 thinking requires concentration and need to be controlled.

3. Methodology

This section presents methodological details related to research set up and data gathering. It must be mentioned that both experimental data and observation outcomes are unstructured in nature. The reason is that the experiment itself did not produce data. In only enabled development of models in four comparable groups. Direct observations had a form of notes and developed models. As this research represented a qualitative type of investigation, experiment settings were simple and number of analysed subjects relatively low. As stated at the end of the previous section, system dynamics is associated with two types of diagrams – causal-loop diagrams and stock-and-flow diagrams. Therefore, the identification of modelling drawbacks was conducted separately for both types of diagrams.

3.1. Causal-loop Diagrams

The development of causal-loop diagrams was conducted by 28 students at the bachelor degree studying Systems Engineering and Informatics study programme. All engaged students received basic information about causal-loop diagram, its notation, main principles, purpose of application. Moreover, these were given several examples. Then, they were allowed to work on the diagram development within 6 lessons during the winter semester of the academic year 2017/2018. As students were beginners, the topic was arbitrary. They had a chance to choose any type of system they are familiar with. In this way, issues with content explanation and information gathering stage of modelling were minimised. However, the complexity of diagram was limited to 15-20 variables.

3.2. Stock-and-flow Diagrams

Similarly to causal-loop diagrams, stock-and-flow diagrams can be used for modelling of large variety of systems. System dynamics has been applied by both practitioners and academicians to study various topics ranging from global warming (Sterman and Sweeney 2007) to health care issues (Allender et al 2015). Therefore, selection of topics suitable for modelling is in fact unlimited. However, engaged students enrolled into the Systems Engineering and Informatics study program had already one semester experience with modelling by means of stock-and-flow diagrams in this experiment phase. In this case the topic selection process was bounded by a general and simple-to-understand topic that had to be taken into consideration. The main modelling theme was associated with a proverb expressing dynamics of two variables – "Hard times produce tough men, tough men enable good times, good times produce unmanly men, unmanly men cause hard times". Hence, students were required to develop structure that would exhibit behaviour in form of oscillation of two main selected variables. Other variables were without any limitations or requirements with respect to their behaviour in time.

There were four types of groups in which modelling took place. However, the purpose of this was not to analyse differences among groups as there was relatively small number of models which disables any type of rigorous statistical processing. The main intention was to capture as many drawbacks as possible. That is why both individuals and teams, and methodology-(un)driven groups were created.

1) Six teams consisted of two or three people. These groups strictly followed methodology of system dynamics models development, starting with topic clarification, system boundary identification, determination of the discriminatory level, preliminary structure draft done with pen and paper, iterative development of stocks and flows with continuous verification etc.)
2) Seven teams consisted of two or three people without any methodological information and limitations. These teams developed models according to their own needs taking any procedure they find appropriate or suitable according to their capabilities.
3) Twenty individuals working with respect to modelling methodology as explained in the first item of this list.
4) Twenty individuals developing models without any limitations as explained in the second item of this list.

Students undertook ten sessions. Each session had 45 minutes available for modelling. These sessions took place during the winter semester of the academic year 2017/2018. Identically to the part of experiment with causal-loop diagrams, engaged students were studying at the bachelor degree of the Systems Engineering and Informatics study programme.

4. Results and Discussion

Fisher (2011) highlights the relationship between systems thinking and system dynamics as a tool helping to transform systems thinking into action. She states that application of system dynamics can be successful only if we are willing to admit that our mental models need to change. This statement describes the main problem that is investigated in this study and further elaborated by real life data presented in this section.

4.1. Causal-loop Diagram

Students developed diagrams dealing with a wide range of topics. Work and study, stress and health status, drug addiction, competition among firefighters, fishing or fitness can serve as examples. However, business- and entrepreneurship-related topics prevailed. Based on the analysis of the developed models, a list of all identified modelling errors is created. As systems thinking represents the main topic of this study, the list is split into two parts. While the first part presents mistakes associated with the absence or insufficient application of systems thinking, the second part enumerates rather technical issues related to models and their development. The errors are presented in no particular order. Their frequency or perceived significance are disregarded.

Systems thinking-related issues:

a) Feedbacks represent the primary drivers of the model development. Instead of developing real structure and consequent identification of main feedbacks, modellers focus on selected loops and build structure around them. This procedure results in a set of large loops consisting of many cause-and-effect relationships with limited number of variables joining one loop with another. In this way, the model seems to be endogenous, but this model attribute is useless if this mistake takes place. However, it is important to note that this type of issue is not quite significant in case of loops with low number of variables. Although the exact demarcating number of variables cannot be determined, it is clear that the higher number of variables in this type of loop, the less systemic approach is applied during its modelling. The non-linear type of thinking is over-emphasised at the expense of other thinking tracks such as operational thinking in this case.
b) The model comprises a higher number of exogenous variables which sometimes form a summative variable that is then used in the model (e.g. "Plastic", "Glass" and "Paper" that are put together to obtain variable "Garbage" – in this case, three exogenous variables are useless in the model). Non-linear type of thinking and dynamic thinking need to be strengthened there.
c) Polarities of loops are incorrectly determined. Although there is an exact procedure for polarity assignment, modellers fail. Moreover, there is a possibility to verify polarity by the interpretation of the loop in practice. Modellers apply it only occasionally, mostly with inability to evaluate meaningfulness of the loop polarity. This incapability is rooted in the insufficient non-linear, operational and analytical thinking.

d) The whole model includes only positive link polarities and positive feedbacks. Although similar systems definitely exist, they are mostly only simple or trivial ones. If this situation appears in more complex systems, something goes very likely wrong. Mostly, a lack of operational thinking results in the development of similar models.

e) Modellers identify and mark all loops that are included in the model. This is perfectly fine if small models are used and modellers are able to interpret all feedbacks and find them significant. The higher complexity of the model, the higher number of loops. Hence, it does not make sense to highlight all of them. Improved application of critical thinking and scientific thinking would be helpful.

f) Modellers capture correlation instead of causality. For instance, the variable "Production" rises and thus the variable "Products sold" increases too due to the positive polarity of the link. However, the former variable can rise without any changes in case of the latter variable. There is only correlation between these two variables while another needs to be added (e.g. "Change in demand"). Critical thinking and dynamic thinking should be more appropriately applied in this case.

g) Modellers include the main topic of the model as one variable in the model structure. In some instances, this can be considered as meaningful only if the variable has its own inputs and outputs. However, the inclusion of this type of variable leads to the development of "black hole" in which all links terminate. The lack of structural thinking usually leads to creation of this structure.

h) Models sometimes do not comprise key variables. There is one example described in the literature pointing out that models describing milk production do not include "Cow" as one variable (Olaya 2015). This type of problem can be found also in some models developed during this study. For instance, a model focused on dynamics of production and sales does not comprise customers. Operational thinking and analytical thinking need to be improved in this case.

i) The inability to determine model boundary represents the last issue associated with causal-loop diagrams in this study. Although there was a limit of 15-20 variables that can be included in the model, some students described it as useless restriction as they wanted to further elaborate their model. This situation indicates inability to apply scientific thinking that suggests the modelling process has to be terminated at a certain point in order to enable analytical stage to start.

Technicalities:

j) Identified loops are not numbered or any other unambiguous identificator such as short name is not used. While numbering can significantly help during reporting or model description, inability to assign name to a loop can indicate problems of the modeller to interpret the role of the feedback in the model.

k) Inappropriate names of variables are used. These are based on modellers' implicit assumptions or insights that others cannot be familiar with. Unsuitable names can be misleading or confusing. For instance, there is a difference between variables "Contract conclusion" and "Probability of contract conclusion" when impact of increased appointments with potential clients is modelled. Similarly, "Maintenance" and "A need for maintenance" clearly expresses what type of change the variable can make.

l) The selection of variables that are inappropriate for monitoring of dynamics such as descriptive variable and related links (e.g. "Web portal") occur. In this case, it is also impossible to set link polarities.

m) Unnecessary intersect of links that visually reduce model readability and clarity are included.

With two exceptions, nearly all errors are included in one diagram presented in Figure 1. First, items g) and h) exclude each other, i.e. it is not possible to have both mistakes in the same model. Therefore, the item h) is not included. Moreover, the item d) does not take place in the diagram as it is difficult to achieve if the diagram from a certain level of complexity is expected to have at least minimum content meaningfulness. The rest of mistakes are visualised in the causal-loop diagram displayed in Figure 1. As complexity of this diagram is not as high, some mistakes do not have to be considered as urgent or significant. However, the higher the diagram complexity, the higher the importance of the issue.

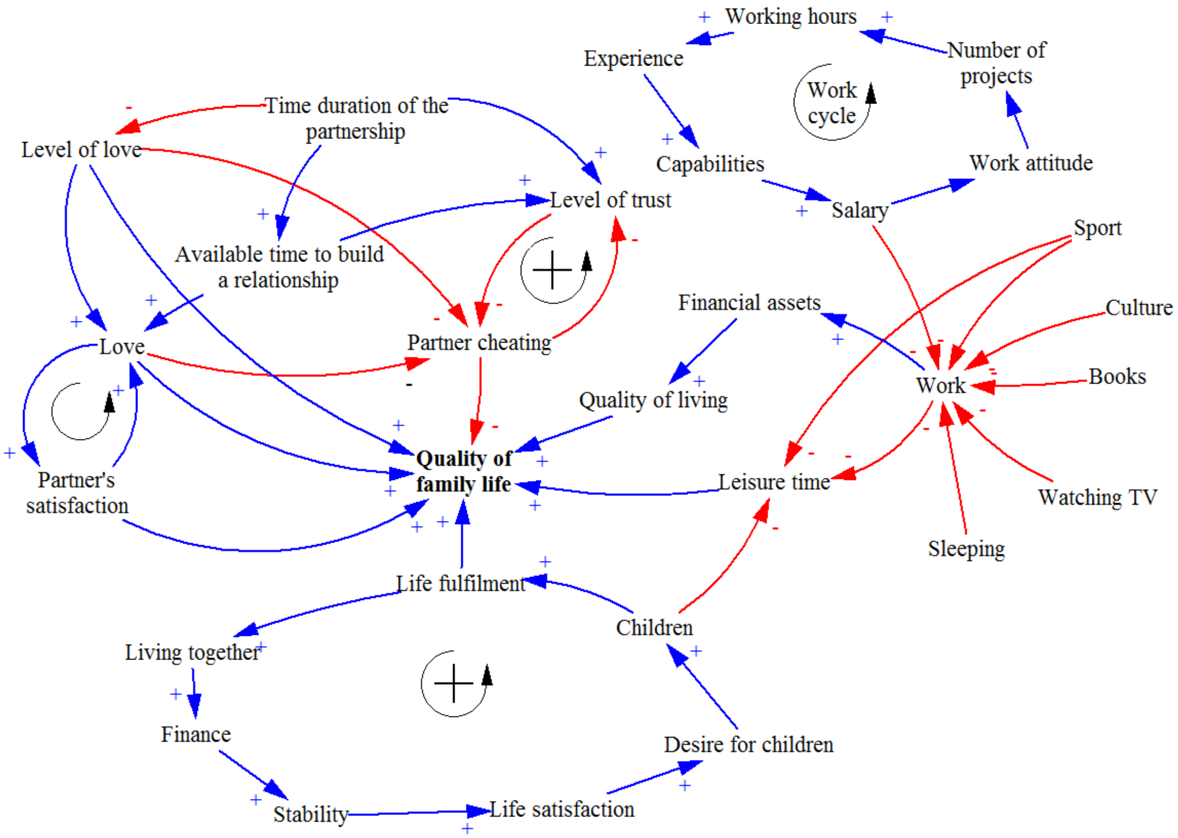

Figure 1. Demonstration of main drawbacks in causal-loop diagrams creation (source: authors' research)

4.2. Causal-loop Diagram

As stated in the Methodology section, there was only one limitation in form of general topic associated with modelling of stock-and-flow diagrams. Regardless this restriction, diverse topics were elaborated in models. Both modelling of general concepts and relationships, and specific instances of the general topic were captured in particular models. Not surprisingly, Lotka-Volterra model is embedded in the most models from the general point of view. In fact, the general topic generates this type of model and its behaviour. Other models such as Kermack-McKendrick model, Jacob-Monod model or Ricker's reproduction equation with time delays are developed. However, these models were created unwittingly as students were not familiar with any of them. These generic models were applied on topics such as infection and immunity, business, warfare, or witch-hunt. Students developed and simulated models that included full range of allowed number of stocks, from three to five stocks. Analogically to causal-loop diagrams, drawbacks associated with stock-and-flow diagrams are divided into two groups.

Systems thinking-related issues:

1) Models have more exogenous variables than necessary. Apparently, this problem is shared by both types of diagrams which confirms the significance of this issue. When exercising closed-loop thinking, people mostly look to the loops themselves as being responsible for generating the behaviour patterns exhibited by a system. This is in contrast with holding some set of external forces responsible for behaviour patterns: external forces tend to be viewed as precipitators rather than causes. While the former is systemic in nature, the latter approach is not. The existence of a high number of exogenous variables is called "Dead buffalo". Similarly to causal-loop diagrams, the lack of both dynamic and non-linear thinking is the issue there.
2) Models contain various stocks that do not create feedbacks. There are only local feedbacks associated merely with one or two stocks. However, larger feedback structures are not developed. Not only do modeller incorporate feedbacks into their structure, they also do not see them. If these models are developed, analytical and non-linear thinking needs to be strengthened.
3) Generic templates described as a methodological hint are not used. The application of these templates ensures that structural thinking is appropriately employed. The lack of structural thinking together with ignoring of templates lead to the development of improper model structures.

4) Although current on-the-shelf software applications for system dynamics modelling include various tools for usage indiscrete variables, modellers very often apply if-then-else function. The main intention is mostly associated with the need to increase the level of granularity applied in their models. However, the deployment of this function indicates inability to use continuous thinking in practice.
5) Sometimes, the variables are linked without the ability of modellers to explain the reason. They link stocks or auxiliaries just because they find it useful. In this case, analytical and critical thinking are applied at insufficient level.
6) There is a need to continually elaborate model and include new variables that are found useful for the model. This indicates the inability to think scientifically as modelling process has to be finished eventually in order to test hypotheses and simulate model behaviour. In addition to this, modellers fail to prioritise relevant variables or exclude them in order to keep the model's complexity at the acceptable level. This represents an issue from the generic and critical thinking perspective.
7) Modellers do not struggle to determine two main variables (stocks). However, they encounter problems when the preliminary version of their models should be extended by the third variable. This means that this is an issue for them create a single loop structure, but more complex structure goes beyond their abilities. Sometimes the application of intuitive thinking would be useful in this case. Moreover, non-linear and operational thinking need to be strengthened.
8) The establishment of a link with incorrect direction cause that models either do not work, or work inappropriately. The occurrence of this error reveals the inability to understand the operational aspects of the system. Operational thinking needs to be improved in this case.
9) Developed models are complex and their behaviours fulfil the expectations, but the units or dimensions of variables are not appropriately synchronised. This means that equations that are recalculated during the simulation do not have to provide the correct outcomes, even though they seem to be acceptable for modellers. Units do not have to be monitored if a modeller has strongly developed structural thinking. However, even with this talent, the development of more complex structures evokes the necessity to explicitly monitor and synchronise units.
10) The application of the Random built-in function is the primary mechanism to force model behave in required manner. It is true that Random function helps to get desired model behaviour. However, once applied, the modeller loses the ability to determine whether the behaviour is produced by model structure, which is what we need, or by generating random inputs (which is not the most appropriate approach). The ability to recognise the source of the behaviour is closely tied to dynamic and analytical thinking. Nevertheless, it does not make sense to train these two types of thinking in order to acquire the ability to use Random function. It is more suitable to support operational and structural thinking.

Technicalities:

11) The recommended way how to develop models is to create as simple version of a model as possible, include initial parameters and simulate it. However, modellers have a tendency to develop the structure in its whole complexity to be sure that they identified variables which they wanted to use in their models. This consequently leads to big issues with model parametrisation.
12) Models sometimes comprise visual drawbacks that make the model less readable and understandable such as intersection of links or overlapping of variable names.
13) Not always do variable names correspond with their intended meaning or content. Then, interpretation of such models or structure is more difficult.
14) Some variables have their own limitations. The impossibility of values to go beyond zero can serve as an example. Modellers omit or ignore these limitations in order to obtain desired model behaviour.
15) Errors in equations and incapability to determine what values will be returned are quite often hidden inside the model structure. These mistakes can be revealed only by the analysis of equations and their meaning in the appropriate part of the model structure.

Needless to say, all errors represent a system as well, i.e. they are mutually interrelated. While one type of mistake can minimise or eliminate another type (e.g. errors g) and h) in case of causal loop diagrams), other types of drawbacks can support and mutually strengthen each other (e.g. errors 3) and 11) in case of stock-and-flow diagrams).

It is possible to find out which types of thinking are the most crucial ones for system dynamics modelling. After analysis of all causal-loop diagrams and stock-and-flow diagrams, the following results are obtained:

- Operational thinking – 7 instances
- Non-linear thinking – 5 instances,
- Analytical thinking – 4 instances,
- Critical thinking – 4 instances,

- Structural thinking – 4 instances,
- Dynamic thinking – 3 instances,
- Scientific thinking – 2 instances,
- Continuous thinking – 1 instance,
- Generic thinking – 1 instance,
- Intuitive thinking – 1 instance.

There are four interesting results that are worthy of notice. First, results indicate that system dynamics modellers struggle with capturing true state of systems and their nature. Operational thinking enables to see systems from the realistic perspective and perceive unbiasedly what they really are and how they really behave. With little of exaggeration, this issue makes one reflecting of the problem whether it is better to make decisions based on inappropriate models or do not make any decision at all. Second, it is not surprising that non-linear thinking holds the second position on the list. Necessity to think in feedbacks and understand non-linearity are the main reasons why systems thinking and system approach were rediscovered approximately a century ago. Apparently, this thinking track has not been fully adopted yet. Third, structural thinking represents the core of system dynamics modelling. Although this type of thinking is supported by majority of available software tool or application (Bureš 2015), control of units or dimensions of single variables is a discipline that can be mastered only during (mostly) painful process of obtaining experience. However, without this ability, developed models can be useless and merely serve as a shallow visualisation of modelled systems. Last, dynamic thinking seems to be surprisingly low on the list. Application of system dynamics is first of all about dynamic thinking and understanding how system behave in time (or better to say, how variables or their values develop in time). Then, the question is, whether it is an issue when an insufficient level dynamic thinking occurs as we build models just because we realise this shortcoming and want to improve it with the help of created models. These four notes are only examples how results of this study can be analysed, interpreted and main benefits determined. However, the same analytical process will definitely identify weak points of the study.

5. Study Limitations and Further Research

Apparently, this study is associated with some limitations. First, low number of subjects and only students of specific field of study were included in the study sample. Business- and entrepreneurship-related topics are prevailing in the set of evaluated models. Very likely, students from different fields of study would select different topics. These might also have different background knowledge which would provide them with the elimination or omitting of the mistakes related to illogical relations and polarities. Moreover, those might be able to identify the key variables easier (or worse) than the study sample. The aforementioned is linked with personal characteristics and the level of experience and dependency of the individuals. These influence significantly the originality of included variables as well as their relevancy. Second, it is almost impossible to avoid mutual consultations among students. Although students were instructed to work individually, experiment could have been under control only in computer labs. Thus, undesirable consultations represent extraneous variable in the experiment. On the other hand, if mistakes are done even after consultation, their significance should be considered as even stronger. Third, the experience of model evaluator has obvious influence as well. Each individual perceives the importance of the mistakes diversely. Moreover, the ability of recognition and categorisation of problems varies a lot as well. Fourth, the topic familiarity impacts the ability of participants to express the comprehensible overview of the modelled system including its relations etc. Among other issues, the used software tool plays its role as well. It has its own logic, settings and features. Some involved students were not satisfied with the tool interface and this fact might have influenced the overall quality, complexity and interpretation of the models. Then, there is a big diversity in models in terms of their content, extent, topic or complexity which makes their analysis more difficult and inaccurate. The last but not least, some mistakes can be corrected by giving enough iterations to modellers to elaborate the same model as this process is iterative. Students probably did not have enough time to do the iterations needed to correct some of the mistakes in 6 sessions.

The list of identified drawbacks is not definitely complete. It is based on the application of specific methodological approach that has its own limitations. Assignment of types of thinking to existing modelling problems in system dynamics are not based on rigorous experiments. The deduction is used as the main method. The application of different experiment settings can lead to results that can complement outcomes of this study. Furthermore, it would be interesting to analyse other types of modelling methodologies and find out if and to which extent single thinking tracks are included or cause the majority of problems. The future research should also include more participants with aim to enhance the revelation of important issues faced during modelling and mistakes within the developed models together with finding their causes. The further research might also investigate in more detail the differences between individual and group work. The question is whether the group projects tend to be more reliable, complex and practical thanks to the member's reflection and correction of inappropriate connections or misleading concepts within the models.

6. Conclusions

Systems thinking represents a skill that needs to be mastered by systems engineers in order to help them to develop meaningful system dynamics models that can support proper decision-making and comprehensive view. The mistakes in the application of systems thinking might cause significant problems and lead in inappropriate and course of action in decisions, predictions, situational analysis etc. This paper introduced some of these issues based on the observation and assessment of the system dynamics model creation. The sample modellers repeated a set of aforementioned mistakes. These were connected either with causal-loop or stock-and-flow diagrams. Moreover, it was possible to link them with particular types of thinking. The provided identification of problematic issues, inappropriate approaches, assumptions or conclusions aims to help modellers and prospect users of models to avoid or eliminate the mentioned mistakes. As revealed in this study, the operational thinking represents the most challenging thinking track. It is followed by non-linear, analytical, critical and structural thinking. Therefore, these skills should be (together with all the other types of thinking) practiced in pursuit to be appropriately used in transformation of the systems thinking in action.

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