Model building in System Dynamics and Discrete-event Simulation: a quantitative comparison

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Abstract
This paper presents an empirical study on the comparison of model building in System Dynamics (SD) and Discrete-event Simulation (DES). We study the model building process of 10 expert modellers (5 SD and 5 DES modellers), who talk aloud while building prison simulation models. The transcripts were coded based on 7 modelling topics: problem structuring, conceptual modelling, data inputs, model coding, validation & verification, results & experimentation and implementation. Our results suggest that all modellers switch between modelling topics, however DES modellers follow a more linear progression than SD modellers. Model coding is a central topic for DES modellers, while conceptual modelling followed by model coding interest SD modellers the most. Interestingly, the combined verbalisations on conceptual modelling and model coding account for almost the same percentage of SD and DES protocols. The *quantitative analysis of expert modellers' behaviour presented in this paper contributes towards the comparison of SD and DES.*

Keywords: system dynamics, discrete-event simulation, comparison, simulation, model building, Verbal Protocol Analysis.

1 Introduction

System Dynamics (SD) and Discrete-Event Simulation (DES) are two simulation approaches that claim a wide range of applications in OR. However they exist as two separate streams, with not much communication between each-other. There are a few studies on the comparison of DES and SD, but work is scarce and usually represents the authors' personal opinions (Brailsford and Hilton, 2001; Morecroft and Robinson, 2005). Therefore, this paper presents an empirical study on the comparison of SD and DES model building process. The comparison is based on the behaviour of expert modellers during a simulation modelling task. We acknowledge that key fundamental differences exist between SD and DES simulation models and the respective software used. However, this is not the scope of the current paper. The objective of this paper is to provide empirical evidence on the differences and similarities in the thinking process during SD and DES modelling.

The current study consists of laboratory experiments, where 10 expert modellers (5 SD and 5 DES modellers) are observed while building simulation models of the UK prison population. We use a qualitative research technique called Verbal Protocol Analysis (VPA), where expert modellers are asked to speak aloud their thoughts while they are undertaking a simulation modelling exercise. Conclusions are drawn based on the live accounts of expert modellers. The aim of this study is to provide a quantitative comparison of the simulation modelling process followed by SD and DES modellers. Our study brings closer the two fields of simulation, with a view to creating a common basis of understanding. The paper is outlined as follows. It starts with a review of the existing literature on the comparison of DES and SD, followed by a description of the study undertaken, where the case study and the research method used, Verbal Protocol Analysis (VPA), are described. We then present the quantitative results of the study, based on observations from 10 modelling sessions. Finally, we discuss the limitations and the main findings of the current study.

2 Existing work on the comparison of SD and DES

In this section, the existing literature on the comparison of two simulation techniques SD and DES is reviewed. Existing work on the comparison of SD and DES is scarce. In the few studies found, comparisons tend to be biased towards either the SD or DES approach. The views expressed consist mainly of the authors' personal opinions based on their own area of expertise (Brailsford and Hilton, 2001). It can be argued that the two modelling approaches are different, but on the other hand the application of both approaches can yield complementary insights (Morecroft and Robinson, 2005). Furthermore, traditionally little dialogue existed between the two modelling communities (Sweetser, 1999; Lane, 2000; Morecroft and Robinson, 2005). However this is currently changing with more academics and practitioners showing an interest for future collaboration between the two fields(Morecroft and Robinson, 2005).

System Dynamics models consist of a system of stocks and flows where continuous state changes occur over time. Whereas Discrete-Event Simulation models systems as a network of queues and activities, where state changes occur at discrete points of time (Brailsford and Hilton, 2001). In SD the entities are presented as a continuous quantity. On the other hand, in DES the objects are individually represented and can be tracked through the system. Specific attributes are assigned to each individual and determine what happens to them throughout the simulation. In DES state changes occur at discrete points of time, while in SD state changes happen continuously at small segments of time (Δt). Specific entities cannot be followed throughout the system. SD models are generally deterministic and variables usually represent average values. DES models are stochastic in nature with randomness incorporated with the use of statistical distributions. Despite the differences listed, it is claimed that the objective of models in both simulation approaches is to understand how systems behave over time and to compare their performance under different conditions (Sweetser, 1999).

First, Coyle (1985) comes into the discussion from a SD perspective, while considering ways to model discrete events in a SD environment. His comparison focuses on two aspects:

randomness existing in DES modelling and the model structure, where it is claimed that open-loop vs. closed loop systems are represented in SD and DES respectively.

In her doctoral thesis, Mak (1993) studies how DES activity cycle diagrams can be converted into SD stock and flow diagrams. Mak also presents a list of fundamental differences between DES and SD modelling.

Coming from a consultancy background, Sweetser (1999) provides a comparison based on the established modelling practice and the conceptual views of modellers in each area. He ends by comparing DES and SD conceptual models of a production process.

Brailsford & Hilton (2001) studied the comparison of DES and SD, applied in health care modelling. The authors compare the main characteristics and the application of the two approaches, based on two specific health-care studies presented (one in SD and the other in DES) and on their own experience as modellers. They conclude with a presentation of the technical differences between the two approaches, providing a list of criteria when each approach is more appropriate.

Lane (2000) gives a thorough comparison between DES and SD, focusing on the conceptual differences. His discussion is again based on his personal experience as a system dynamicist. Lane considers three modes of discourse, where it is argued that DES and SD can be presented as different or similar based on the position taken (the mode of discourse). At the end, Lane provides a list of conceptual differences, taking a mutual approach. However, Morecroft and Robinson (2005), disagree with some of the statements made. Theirs is the first study where the comparison is based on empirical work, a common fishery model. The authors built a step-by-step simulation model, using SD (Morecroft) and DES (Robinson) modelling. However, one could claim the existence of bias, as the two modellers were aware of each other's views on modelling.

An empirical study on the comparison of DES and SD from the users' point of view was carried out by Tako and Robinson (Forthcoming). The authors found that users' perceptions of two simple DES and SD models were not significantly different. So far, we have not yet identified any study that provides a self-contained and independent comparison of the SD and DES model building process. Therefore, the objective of this paper is to present an empirical study on the comparison of DES and SD model building process and to provide insights for both areas of simulation.

3 The study

The current study consists of an empirical research comparing DES and SD involving simulation modellers. We compare the DES and SD model building process, using Verbal Protocol Analysis (VPA), a qualitative research method. For the application of the empirical work, we use a case study on the UK prison population.

The overall objective of this study is to empirically compare the behaviour of expert modellers while undertaking a simulation modelling task. We believe that DES and SD modellers think differently during the model building process. Therefore, it is expected that while observing SD and DES expert modellers building simulation models, these differences become evident. The authors use qualitative and quantitative text analysis to identify these differences. However, the current paper focuses only on a quantitative comparison of expert modellers' thinking, looking at the process they think about while building simulation models. The aim is to identify whether SD and DES modellers attend to similar modelling stages and to what extent. Timeline plots based on Willemain (1995) are created following the attention paid by each participant to a set of topics during a modelling session. In addition the percentage of attention paid to each modelling topic is measured.

3.1 The case study

A suitable case study for the purposes of this research needs to be sufficiently simple to enable the development of a model, which can be built in a short period of time (60-90 minutes). In addition a suitable case study had to accommodate models from both simulation techniques, so that the specific features of each technique (randomness in DES vs. deterministic models in SD, the aggregated presentation of entities in SD vs. the individual representation of entities in DES, etc.) would be present in the models built. Among others, we were interested to see how the same aspects of the problem would be represented with each simulation approach (e.g. feedback). After considering a number of possible contexts, the prison population problem was selected. The prison population case study, where prisoners enter prison initially as first time offenders and then return back to prison as recidivists can be represented by simple simulation models, using both DES and SD. Furthermore, the prison population has already been modelled using each simulation approach. DES models of the prison population have been developed by Kwak et al. (1984), Cox et al. (1978), Korporaal et al. (2000), and a SD model has been developed in Bard (1978). Therefore, we consider the UK prison population case study as suitable for this research.

The UK prison population case study used in this research is based on Grove et al. (1998). The case study starts with a brief introduction to the prison population problem with particular attention to the issue of overcrowded prisons. Following, were descriptions of the reasons for, and impacts of, the problem. The figures and facts used in the case study are mostly based on reality, but slightly adapted for the purposes of the research.

In the case study two types of prisoners are involved, petty and serious offenders. There is already an initial number of prisoners in the system (76,000). Offenders enter the system as first time offenders and receive a sentence depending on the type of offence. Petty offenders enter the system at a higher rate, on average 3,000 people/year vs. 650 people/year for serious offenders, but receive a shorter sentence length, on average 5 years vs. 20 years for serious offenders. After serving time in prison the offenders are released. A proportion of the released prisoners re-offend and go back to jail (recidivists) after on average 2 years. Petty prisoners are more likely to re-offend. However, these numbers were intentionally not given to the modellers, who were expected to either make their own assumptions or ask for further data. For more details on the case study refer to Tako and Robinson (Forthcoming).

In order to solve the situation two possible scenarios are considered, either to increase the current prison capacity and so facilitate the introduction of stiffer rules, or the alternative of reducing the size of the prison population by introducing alternatives to jail and/or enhancing the social support provided to prisoners. The task for participating modellers was to create a simulation model, which would be used as a decision-aiding tool by policy makers.

3.2 Verbal Protocol Analysis (VPA)

In the modelling sessions we use Verbal Protocol Analysis (VPA), originally derived from psychology (Ericsson and Simon, 1984). Willemain (1994; 1995) was the first to use VPA in Operational Research (OR) to document the thought processes of OR experts during model formulation. Building on Willemain's initial work, Powell and Willemain (2007) and Willemain and Powell (2007) used VPA to study the model formulation processes followed by novice modellers in OR, with the view to gain insights about the best way to teach OR to students. VPA is a qualitative research method that requires the subjects to 'think aloud' when making decisions or judgements during a problem-solving exercise. It relies on the participants' generated verbal protocols in order to understand in detail the mechanisms and internal structure of cognitive processes that take place (Ericsson and Simon, 1984).

VPA is considered to be an effective method for the comparison of the SD and DES model building process. It is useful because of the richness of information and the live accounts it provides on the experts' modelling process. Another option would have been to observe real-life simulation projects, using SD and DES, throughout the modelling process. However, observing real life projects was not suitable for the timescales of this research. Evidence suggests that simulation projects can take between one and three months, for a typical project, or even longer (Robinson, 2004). In addition, for a valid comparison it was necessary to have comparable modelling situations. We also considered running interviews with modellers from SD and DES area. However, we believe that modellers' reports would not represent the full picture of model building. Also modellers' reflections may not correctly reflect the processes they follow during the model building process. Whereas using VPA it is possible to capture modellers' thoughts, as part of a controlled experiment, using a common stimulus – case study.

Protocol analysis as a technique has its own limitations. The verbal reports may omit important data (Willemain, 1995) because the experts being under observation may not behave as they normally would. The modellers are asked to work alone and this way of modelling may not reflect their usual practice of model building, where they would interact with the client, colleagues, etc. In addition, there is the risk that participants do not 'verbalise' their actual thoughts, but are only 'explaining'. To overcome this and to ensure that the experts speak their thoughts loudly, short verbalisation exercises, based on Ericsson and Simon (1984) were run at the beginning of the sessions.

The subjects involved in this case were provided with the prison population case study at the start of the VPA session and were asked to build simulation models based on it using their preferred simulation approach. During the modelling process experts were asked to speak their thoughts - to 'think aloud' as they model. The researcher (Tako) sat in the same room, but social interaction with the subjects was limited and she only intervened in the case that participants stopped talking for more than 20 seconds to tell them to "keep talking". The researcher was also answering explanatory questions and provided participants with additional data inputs (if they asked for them) and also prompted them to build a model on the computer in the case when they did not do so by their own initiative. The modelling sessions were held in an office environment with each individual participant. The sessions lasted approximately 60-90 minutes. The participants had access to writing paper and a computer with relevant simulation software (e.g. Simul8, Vensim, Witness, Powersim, etc.). The protocols were recorded on audio tape and then transcribed.

3.3 The subjects

The subjects involved in the modelling sessions were 10 simulation experts in SD and DES modelling, 5 in each area. The sample size of 10 participants is considered reasonable, although a larger sample would be better. According to Todd and Benbasat (1987), due to the richness of data found in one protocol, VPA samples tend to be small, between two to twenty.

For reasons of confidentiality participants' names are not revealed. In order to distinguish each participant we use the symbol DES or SD, according to the simulation technique used, followed by a number. So SD modellers were called SD1, SD2, SD3, SD4 and SD5, while DES subjects DES1, DES2, DES3, DES4 and DES5. All participants use simulation modelling (SD and DES) as part of their work and have at least 4 years of experience in modelling. All participants were modellers with high experience in modelling, most of them holding consultant posts in different organisations. The companies they come from are established simulation software companies or consultancy companies based in the UK.

A mixture of backgrounds within each participant group (DES and SD) was sought. All participants have completed either doctorates or masters' degrees in engineering, computer science, Operational Research or hold MBAs. Their experience in modelling ranges from at least 6 years up to 19 years. They have also acquired supplementary OR and simulation training as part of their jobs. They boast an extensive experience of modelling in areas such as: NHS, criminal justice, food & drinks sector, supply chain, etc.

3.4 Coding of transcripts

A coding scheme was designed in order to identify what the modellers were thinking about in the context of simulation model building. The coding scheme was devised following the stages of typical DES and SD simulation projects, based on Robinson (2004), (Sterman, 2000) and (Randers, 1980). Each modelling topic has been defined in the form of questions corresponding to the issues addressed. The modelling topics and their definitions are as follows:

1. Problem structuring: What the problem is about? What are the objectives of the project?
2. Conceptual modelling: What are the parts of the model? What should be included in the model? How to represent people? How are the variables defined?
3. Data inputs: How modellers refer to data inputs? How are the already provided data used? Are modellers interested in randomness? How are data derived? Do modellers ask for additional data?
4. Model coding: How is the model code created? How is the initial condition of the system modelled? What sort of unit (time or measure unit) is used? Does the modeller refer to documentation? How to model the user interface?
5. Results & Experimentation: What are the results of the model? What sort of results the modeller is interested in? Are modellers interested in achieving equilibrium? What sort of scenarios they run?
6. Implementation: How will the findings be used? What learning is achieved?
7. Validation & Verification: What has gone wrong? Why the model is not working? Are the results correct? Are modellers checking the model against the conceptual model?

The data collected from VPA consist of one verbal protocol for each participant. After transcribing the recorded information, the protocols are divided into episodes or 'thought' fragments, where each episode is the smallest unit of data, meaningful to the research context. Each episode is coded into one of the 7 modelling topics or an "other" category for conversation that was not related to the modelling task. Due to space limitations some examples for only 4 modelling topics are provided below.

Problem structuring:
"The purpose of the model is to test the strategy …" (SD1)
"…it looks like the aim is probably something to do with the reduction of recidivism and the reduction of inflow into the prison system in the first place." (SD2)

Conceptual modelling:
"so we need some sort of process for re-offending, which needs to take place every year." (DES3)
"So I guess, I would probably actually do it [conceptual diagram] on paper, but for simplicity reasons I will start drawing it in Powersim." (SD3)
"So what's going in to serious would be … let's call them new serious," (SD4)

Model coding
"I'm going to set a label in here as well. If they are re-offending I'm going to set minimum wait time label on them, so I'm going to say: set a new label called mmm…" (DES2)
"therefore the monthly rate is that divided by 12." (SD4)

Data inputs:
"Do we have only one piece of information that tells us the period before re-offending is 2 years before re-offend?" (SD1)

"Beyond that, we can call it 20% of serious prisoners re-offending for the sake of argument." (DES4)

We coded the transcripts manually. Automatic coding was not considered appropriate. We based our coding on the context that the participants were talking about, so subjectivity in the interpretation of the scripts was unavoidable. In order to deal with subjectivity, the transcripts were recoded twice after a period of 3 months after the first coding. Overall, there was 81% agreement between the two sets of codings, which we considered acceptable. We then examined the differences and came up with combined coding, which was later on blind checked by a third person, knowledgeable of OR modelling and simulation. In the cases where the coding did not agree, we went through discussions and re-examined the episodes to arrive at consensus coding. Overall, a 90% agreement between our codings was achieved. We undertook a final examination of the coded transcripts to arrive at the final coded protocols, which are analysed in this study.

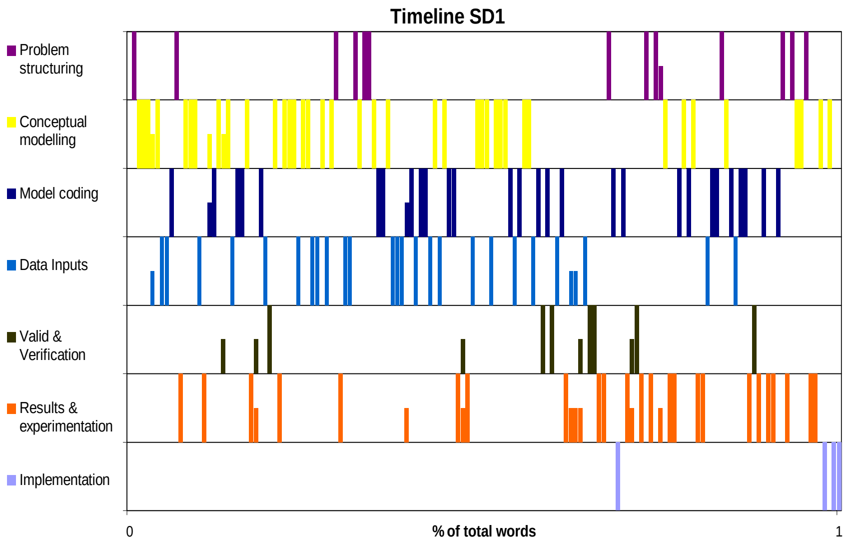
4 The results

This section presents the results of a quantitative analysis of 10 coded protocols. The data represent a quantitative description of participants' modelling behaviour, exploring the modelling topic the modellers attend to and when during the model building exercise. The number of words articulated is considered as a suitable measure of the amount of verbalisation by the modellers. In turn this is used to indicate the amount of their attention to the different modelling topics.

4.1 The timeline plot by modelling topic

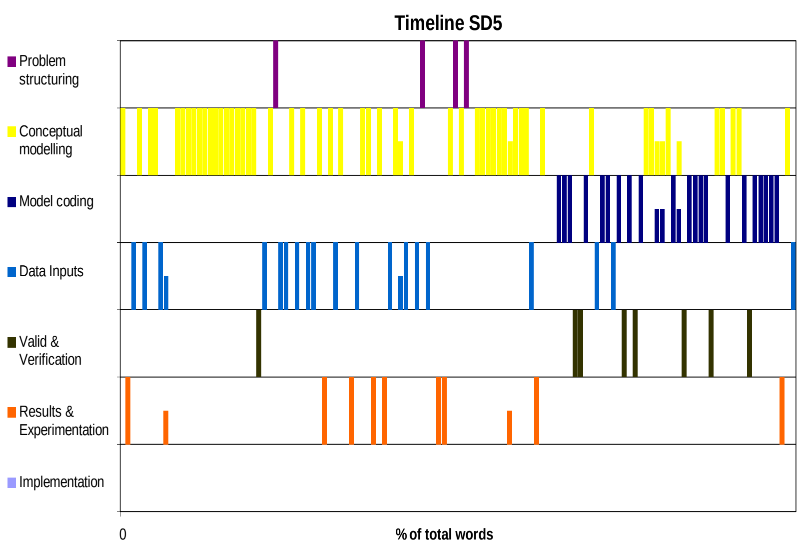
The consecutive episodes in a verbal protocol are presented in timeline plots. A timeline plot consists of a matched set of 7 timelines showing which of the seven modelling topics the modeller is attending throughout the duration of the modelling exercise. The vertical axis is a binary, taking the value 1 when the modelling topic is attended by the modeller, 0.5 when two modelling topics apply and 0 otherwise. The horizontal axis represents the proportion of the verbal protocol, from 0 to 1 (100% of the number of words). The proportion of the verbal protocol is counted as the fraction of the cumulative number of words for each consecutive episode over the total number of words in that protocol, expressed as a percentage. It is important to mention that the timeline plots depict only the frequency that a modelling topic is mentioned by the modeller and not the absolute attention paid to this topic during the modelling task.

In graphs 1 to 4 a sample of 4 timeline plots is presented showing how the attention of expert modellers (SD1, SD5, DES1 and DES5) evolved throughout the duration of the model building exercise by modelling topic. Observing these plots it is obvious that modellers switched frequently their attention among topics. The same pattern of behaviour is followed by expert modellers as in Willemain's (1995) study when modelling a generic OR problem. However, looking at the overall tendencies in the DES and SD timeline plots, one can observe that the DES protocols follow a more linear progression in the sequence of modelling topics. While in SD protocols, modellers' attention is more scattered throughout the model building session.



Graph 1: Timeline by modelling topic for an SD modeller (SD1).

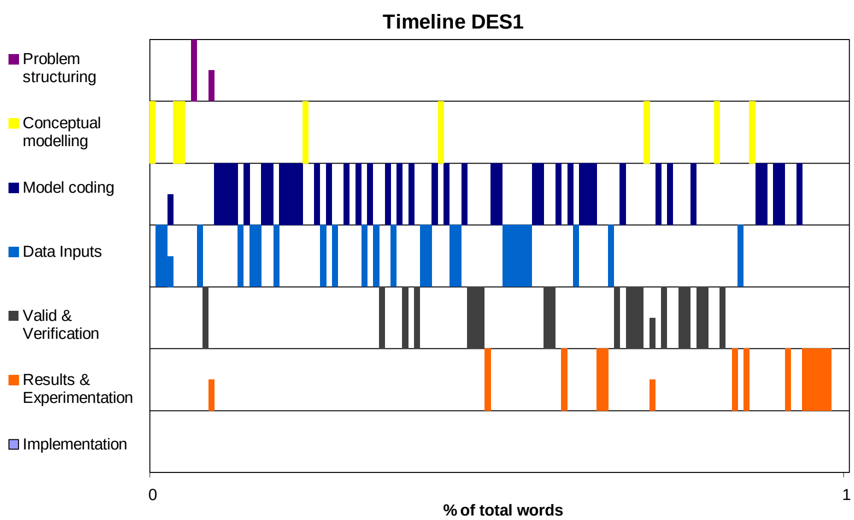
Looking more closely at each topic in the timelines in figures 1 through 4, a number of observations can be made. Considering Problem structuring, one would expect that this would be the first topic to think about before starting any modelling task. In most SD protocols Problem structuring quotes were scattered at random points of time, either at the beginning, middle or even towards the end of the exercise. In the case of DES protocols, Problem structuring is not always a topic modellers thought about. However, whenever mentioned, expert DES modellers tend to consider it at the first stages of the modelling task. In one case only, in the case of DES5, problem structuring quotes were mentioned towards the middle and the end of the protocol. We tend to believe that this is a distinctive case in DES, and therefore we conclude that SD modellers have a tendency to return to problem structuring throughout the modelling task, whereas DES modellers will most probably think about it at the beginning.



Graph 2: Timeline by modelling topic for an SD modeller (SD5).

Regarding conceptual modelling, it can be observed that fewer quotes appear in DES protocols, whereas in SD protocols such quotes are more prevalent. The fewer conceptual modelling bars in the DES timeline plots protocols suggest that DES modellers think less about the structure of the model than SD modellers do. Furthermore in most cases, including both DES and SD modellers, the conceptual modelling is referred to throughout the modelling session, with a higher density in the first or middle stages of the task duration, especially in the case of SD protocols.

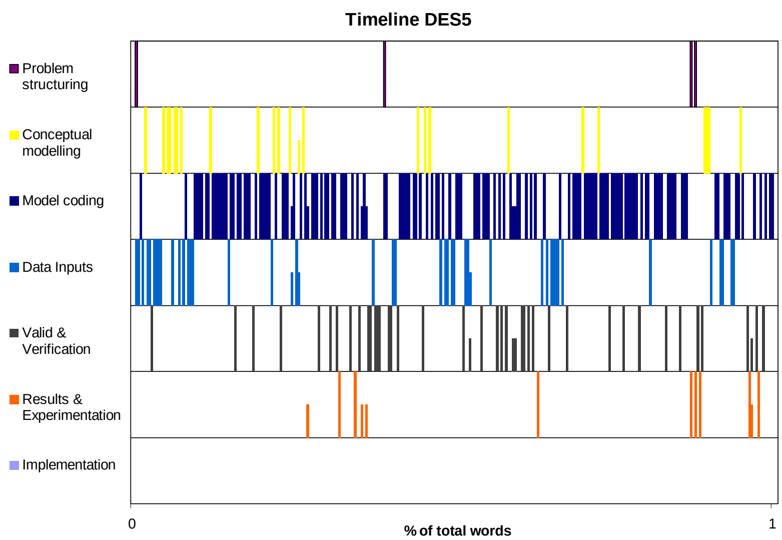
Exactly the opposite picture to conceptual modelling can be observed in the case of the model coding topic. The higher density of model coding bars in the DES timelines (graph 3 and 4) suggests that DES modellers focus more on model coding rather than on conceptual modelling. Compared to conceptual modelling, SD modellers pay less attention to model coding implying that during that not many significant cognitive processes are involved. Indeed on one occasion, SD5 clearly points this out, by mentioning that *"feeding the model into the computer [coding the model] is more or less a mechanical task"*. Furthermore, DES model coding is alternated mostly by data inputs and validation & verification. In the case of SD modelling, model coding is mostly alternated by conceptual modelling and data inputs.



Graph 3: Timeline by modelling topic for a DES modeller (DES1)

Referring to the aspect of data inputs, it can be observed that a roughly similar interest is shown to this topic by all modellers (DES and SD). Contrary to what was expected, it became obvious that during the modelling task, SD modellers required specific and concrete data as much as DES modellers did. Indeed SD5 emphasised the need for collecting the numbers for the variables created during the conceptual modelling stage, "*what I need is the numbers, and once I have the numbers, then I can actually model this"*. Therefore, this suggests that data inputs, is a topic of similar importance for both DES and SD modellers. One difference noticed between SD and DES modellers was that in the case of DES modellers, data inputs topics were mostly alternated by model coding topics, while in the case of SD modelling it was mostly alternated by conceptual modelling and less by model coding topics. This difference is especially obvious in the case of SD5. This suggests that SD modellers think about data inputs while building the conceptual model, whereas DES modellers when they are actually building the model on the computer.

Validation and verification (V&V) is considered to be as important for SD modellers as for DES modellers, to ensure that a valid and accurate model is created. In both groups of expert modellers, V&V quotes are quite scattered throughout the protocols. However in DES protocols we can observe a tendency of V&V topics appearing towards the end of the modelling task. Looking more closely, in the SD protocols V&V topics are mostly alternated by conceptual modelling, data inputs and less by model coding. While in the case of DES protocols, V&V topics are mostly alternated by model coding and less by data inputs and conceptual modelling. Consequently this suggests that DES modellers focus more in verifying the computer code and making sure that the model is correct. The fact that they pay more attention to model coding, could explain this phenomenon.



Graph 4: Timeline by modelling topic for a DES modeller (DES5).

Model results and experimentation topics appear towards the end of most DES and SD protocols. Comparing SD and DES timeline plots, model results and experimentation appear more often in the SD protocols. This implies that SD modellers think more often about issues such as: model results, presentation of results, scenarios, etc. compared to DES modellers. In the case of SD modellers, the pattern of modellers' attention varies from modeller to modeller, however it is clear that modellers think about results or experimentation at random times during the modelling task. DES modellers (excluding modeller DES3) think about this topic towards the end of model building.

Implementation quotes were very rare in all protocols. Nevertheless, more SD modellers thought about implementation, compared to DES modellers, where only modeller DES3 mentioned it during the15th percentile of the modelling task. In the case of SD modellers, implementation topics appear towards the end of the protocols. Even though, there is not much scope for model implementation, in the context of the current exercise, this suggests that most SD modellers (4 out of 5), consider the implications of their models and their use towards the end of the modelling task.

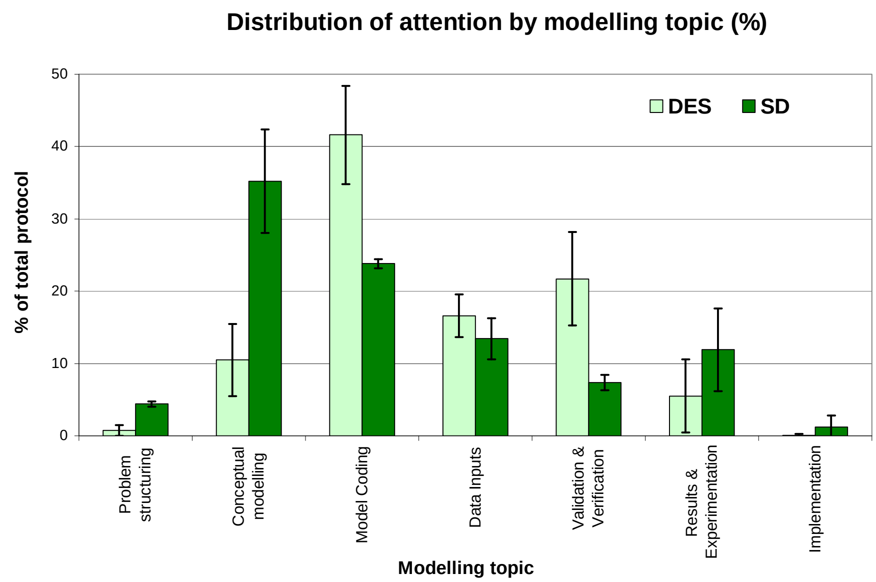
4.2 Percentage of attention

Further to exploring the progression of modellers' attention to the different modelling topics, in this section the distribution of attention by modelling topic is measured. Table 1 presents the respective average word count by modelling topic and the resulting differences for the two groups of modellers. The standard deviation, as a measure of the variation of verbalisations for each modelling topic around the mean is also calculated. It is observed that the overall number of words in the average DES and SD protocols differs by 1,681 words, suggesting that DES modellers verbalised more than SD modellers. Considering each modelling topic separately, the biggest differences between the average DES and SD protocols, can be identified with regards to model coding and validation and verification. It is suggested that DES modellers spend more effort in coding the model in the computer and validating or verifying it, while SD modellers spend more effort in conceptualising the mental model. Furthermore, estimations of the standard deviation suggest that the amount of verbalisation among the DES protocols varies the most. This is shown by the higher value of the standard deviation in 5 DES protocols, being 2,631 words compared to 794 words for the SD protocols. Among the modelling topics, the highest variation in the DES protocols is observed for model coding, conceptual modelling, data inputs and verification & validation. While in the SD protocols the highest variation in the verbalisation of the 5 modellers was observed for conceptual modelling.

Table 1: Average number of words and standard deviation calculated for each modelling topic for DES and SD protocols.

	DES		SD		Assumed differences
	Average words	Standard deviation	Average words	Standard deviation	
Problem structuring	44	51	158	164	-114
Conceptual modelling	664	634	1,350	1,563	-686
Model Coding	2,336	1,396	912	391	1,424
Data Inputs	869	331	514	191	355
Validation & Verification	1,108	434	273	51	835
Results & Experimentation	259	178	427	222	-168
Implementation	8	17	48	72	-40
Other	172	79	96	60	76
Total protocol	5,460	2,631	3,779	794	1,681

Graph 5 represents the percentage distribution of attention by modelling topic, where a similar pattern is observed. The biggest differences are found in the percentage of attention paid to model coding, conceptual modelling, validation & verification and results & experimentation. On average, DES modellers devote 42% of attention to model coding, with the next most attended to topics being verification & validation (22%) and data inputs (17%). Meanwhile for SD modellers, conceptual modelling, counting for 35% of their attention, was the topic of highest interest followed by model coding (24%), data inputs (13%) and results & experimentation (12%). This suggests that DES modellers concentrate their attention more on model coding, leaving 58% of attention to other topics, while the attention of SD modellers is distributed more evenly among topics. Interestingly, the combined attention to conceptual modelling and model coding accounts respectively for 53% and 59% of the overall DES and SD protocols, where the rest 47% or 41% of the protocols focuses on other aspects of simulation modelling. This suggests that both DES and SD modellers spend almost the same amount of time in structuring the model, either conceptually or on the computer.



Graph 5: Average percentage of attention paid to the 7 modelling topics, by DES and SD modellers and mean +/-2 SE.

5 Discussion and concluding remarks

This paper presents a quantitative comparison in the behaviour of expert SD and DES modellers when building simulation models. The contribution of this paper lies in that it provides an empirical study in the comparison of SD and DES model building process.

One of the main findings of this study is that expert modellers do not follow an order of steps during the model building process. This is consistent with Willemain's (1995) findings about the nonlinear behaviour of expert modellers. It was also found that DES modellers follow a more linear progression through the modelling topics, whereas SD modellers' attention is more scattered between topics throughout the modelling task. In the SD scripts it is more obvious that modellers' attention jumps from various stages of model building to the other in a cyclic form. For example most SD modellers (apart from SD5) jump from conceptual modelling to model coding or data inputs and then go back to conceptual modelling to add further parts into the model. To put this into context, most SD modellers started with creating the basic model, including the flow of two types of prisoners entering the model, the stock of prisoners and the outflow of prisoners being released, and after that returned back to problem structuring and to conceptual modelling to add further components in the model. DES modellers tended to create all the parts of the model and then enter the data in the computer, and after having validated the model they would go back to change the model on the computer. Less often did they go back to conceptual modelling. This is consistent with the SD and DES literature, where it is suggested that simulation modelling is a repetitive and an iterative process (Sterman, 2000; Robinson, 2004). However, our findings suggest that different styles of iterations are observed for SD and DES modellers. In addition, it is found that SD modelling is a more iterative process compared to DES modelling. For future research, these preliminary observations will be further explored by analysing SD and DES modellers' transition of attention among topics. Furthermore, similar patterns of attention to the 7 modelling topics were observed amongst the SD modellers compared to DES modellers, where a higher variation among modellers was established.

Another significant finding of this study is that model coding is a central topic that attracts the attention of DES modellers, whereas SD modellers pay the most attention to conceptual modelling and less to model coding. This could be because DES model coding is more complicated compared to SD, which could be related to the respective modelling software and internal coding logic. The use of drag and drop facilities is becoming more widely available in both SD and DES software. However, more flexibility and power is provided by DES software, where different model aspects can be added using some lines of code or functions. These are not obvious to the end user and one needs to be knowledgeable about the software to be able to use these. On the other hand, most SD software tend to have an easier layout and user interface, where different modelling components are available on the screen as well as a choice of equations and relationships between variables.

Another observation made in this study, is that most modellers (with the exception of DES3) did not consider alternative modelling approaches before modelling. This conveys that modellers use the simulation approach they are more familiar with rather than the approach that is considered most appropriate. This study provides an understanding of the modelling processes SD and DES modellers think about while building models. It could be suggested that a combined use of both approaches would be useful to modellers. For example, DES modellers entering into the SD world might be motivated to think more in terms of conceptual modelling. On the other hand, it could be suggested that while knowing both approaches one would be able to choose between the two, depending on the problem situation, time available or client requirements.

However, there are a few limitations to this study, which should be considered. First of all, the data are derived from artificial laboratory settings, where the modellers at times felt the pressure of time or the pressure of being observed. The task given to the participants was a simple and a quite structured task to ensure completion of the exercise for a limited amount time. These factors have to some extent affected the smaller amount of verbalisations for modelling topics such as: problem structuring, results & experimentation and implementation. Observation of real-life modelling projects could provide more representative accounts of DES and SD modellers' behaviour. A bigger sample size could have also provided more representative results, however due to project timescales this was not feasible. In this study only one case study was used. For future research, the use of more case studies could provide more representative results regarding the differences between the two modelling approaches. The accuracy of results could have been affected by the differences between the modellers involved in the study. Even though expert modellers with more than six years experience in simulation modelling were involved, differences such as background, education, level of experience, etc. were difficult to control. In addition, most of the modelling sessions were run under different conditions and time periods, which could have affected the accuracy of the protocols. However, we believe that the protocols derived are representative of each field. For example, SD modellers' verbalisations on conceptual modelling were uniformly higher than DES modellers' verbalisations on the same modelling topic. In this study, experts in either SD or DES have been involved. However, with the increased exposure to both modelling approaches, in the future it would be useful to experiment with modellers who use both approaches in order to observe whether the adoption of both approaches would result in different modelling behaviour.

This is the only empirical study that compares SD and DES model building based on data gained from experimental exercises involving expert modellers themselves. In this paper, we provide only a quantitative description of expert modellers' thinking process. With this quantitative analysis, we studied the processes that SD and DES modellers think about while building simulation models. This work may ultimately help in the selection of the appropriate simulation approach to model a particular problem situation, albeit specific answers are not provided. The authors therefore believe that the comparison presented in this paper contributes towards the selection between the two simulation approaches. For future research the authors will take this study further with an in-depth qualitative analysis of the 10 verbal protocols. The qualitative analysis intends to identify differences in the underlying thought processes between SD and DES modellers. The models created will be further analysed to compare the insights gained.

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