Extending the Meta Model for Enterprise Systems Dynamics from a Software Tooling Perspective

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Keywords: Systems Dynamics, General Ontology Specification Language, Enterprise Governance, Causal Loop Diagram, Stock Flow Diagram.

Abstract: Literature indicates that systems dynamics (SD) has the potential of modelling the behaviour of a system to understand enterprise behaviour and the effect of enterprise policies to address multiple performance areas. Since SD concepts are ill-defined, a meta model for enterprise systems dynamics (MMESD) was developed, using the general ontology specification language (GOSL). The first version of the MMESD was applied to an existing case within the car industry, where the case was modelled with the software named Vensim. The MMESD was developed without considering meta model implementations within multiple SD software tools. This article investigates the use of SD concepts in different SD software tools, highlighting the differences in the use of symbolic formalisms. The main contribution of the paper is extracting new concepts when we compare existing software tools, identifying concepts that are not already reflected in the first version of MMESD. We use the results to further extend the first version of MMESD, and apply an extended second version of MMESD to an existing teacher education faculties case in Croatia as a demonstration. The paper concludes with suggestions for future research.

1 INTRODUCTION

Enterprises are complex socio-technical systems that need to address ill-defined problems that are difficult to solve (Giachetti, 2010; Hoogervorst, 2018). Two disciplines, each with a different approach, aim at understanding both the complexity of enterprises, as well as the ill-defined problems that exist.

Systems dynamics (SD) is used to understand the nonlinear behaviour of complex systems, including enterprise systems, over time, using concepts such as stocks, flows, internal feedback loops and time delays (Meadows, 2008; Sterman, 2002). Since SD modelling helps to understand both functions and behaviour (Forrester, 2007), the models assist in understanding counterintuitive behaviours of a complex system, identifying leverage points to intervene in a system (Meadows, 1999).

Enterprise engineering (EE) as a discipline, furthers the creation of scientific rigor in developing and testing theories, contributing towards a sound body of knowledge in EE (Dietz et al., 2013). One of the knowledge areas within EE, called *enterprise architecture* (EA), provides "a coherent and consistent set of principles that guide enterprise design" (Hoogervorst, 2018, p. 314). Although the principles assist in creating a coherent enterprise design, enterprises pose high conditions of uncertainty that require additional mechanisms to know "what to do" to improve existing performance (Hoogervorst, 2018).

We believe that a systematic understanding of enterprise systems behaviour, could direct attention to enterprise change initiatives when re-designing enterprise design domains. Other authors also motivated the need for shared mental models to integrate SD and EE (Schneider, Gschwendtner, & Matthes, 2015) where SD is useful to indicate decision effects, identifying principles that could guide the evolution of the enterprise constructional landscape. Multiple techniques are available to represent and understand the behaviour of a system, some are more qualitative in nature, such as the causal loop diagram (CLD) and others more quantitative,

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Hussain, H. and de Vries, M.
Extending the Meta Model for Enterprise Systems Dynamics from a Software Tooling Perspective.
DOI: 10.5220/0012173000003598
In *Proceedings of the 15th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management (IC3K 2023) - Volume 2: KEOD*, pages 50-61
ISBN: 978-989-758-671-2; ISSN: 2184-3228

such as stock and flow diagrams (SFD) (Barbrook-Johnson & Penn, 2022). The CLD, also called an influence diagram, system map or sign graph, is used during the early phases of SD and converted into a SFD to enable simulation (Barbrook-Johnson & Penn, 2022). Some academics (Burns, 2001; Sterman, 2000) suggest the early conversion of CL concepts into SD concepts to portray both qualitative and quantitative behaviours on a single diagram that we label a causal loop stock flow diagram (CLSFD), facilitated by some software tools, such as Vensim.

CLDs are however ambiguous, lack detail and are difficult to conceptualize (Binder, Vox, Belyazid, Haraldsson, & Svensson, 2004; Lane, 2008; Schaffernicht, 2010; Tulinayo, van Bommel, & Proper, 2012). When CLD concepts are converted in SFDs, software vendors may use their own symbols to represent the concepts. As an example, STELLA provides additional sub-types for the "stock" entity type, namely a reservoir, conveyor, queue, and oven. The discrepancy between the graphical representations, was also observed by Ventana Systems (n.d.), suggesting a way to convert STELLA stock and flow diagrams into VENSIM.

Based on the premise that EE may be informed by SD to support better decision-making on where to focus actions and re-design efforts, we suggested the use of the *general ontology specification language* (GOSL) to provide additional clarity on the concepts that are used in SD, developing a meta model for enterprise systems dynamics (MMESD) with a summarised set of guidelines to guide the user to design a comprehensive CLSFD. In previous work the MMESD was instantiated, applying the concepts to an existing car industry case (De Vries & Dietz, n.d.). The MMESD was developed without considering meta model implementations within multiple SD software tools. This article investigates the use of SD concepts in different SD software tools, highlighting the differences in the use of symbolic formalisms, and supporting new concepts. The main contribution of the paper is extracting new concepts when we compare existing software tools, identifying concepts that are not already reflected in the first version of MMESD. The extended version of the MMESD is applied to a teacher education faculties case in Croatia based on Tomljenovic et al. (2022).

The remaining article is structured as follows: Section 2 provides additional background on GOSL, and design science research that was used to define the current MMESD version. Section 3 presents an evaluative comparision of the different symbolisms used in some of the common modelling tools, used in SD. Using the identified differences, section 0 follows with an extension of the MMESD. Section 5 provides a demonstration for the extended MMESD using a teacher faculty enrolment policy case in Croatia. The paper concludes with section 6 with key findings, limitations, and recommendations for future work.

2 BACKGROUND

An ontology *specification language* is a *general* specification language to express conceptual schemas, whereas each conceptual schema will be used to capture only intended models, i.e., a particular perspective as an approximation of the real world.

2.1 Ontology Specification Languages and GOSL

Multiple ontology specification languages exist. OntoUML is an emerging language whose meta-model has been designed to comply with Guizzardi's Unified Foundational Ontology (UFO) (Guizzardi, Figueiredo, Hedblom, & Poels, 2019), where users of the previous Bunge Wand Weber (BWW) ontology, have switched to UFO since 2005 (Verdonck & Gailly, 2016). Other languages also exist on a general level, such as entity relationship (ER) modelling (Chen, 1977), and the unified modelling language (UML) (Scott, 2001). A fairly new ontology specification language, the General Ontology Specification Language (GOSL) presented by Dietz & Mulder (2020), has been applied primarily within the EE discipline to define a schemas for a EE-related models. Other ontology languages, such as the Web Ontology Language (OWL), focus specifically on integrating information over the web, rather than defining schemas for EE-related models (McGuinness & Van Harmelen, 2004).

Dietz & Mulder (2020) present the *general ontology specification language* (GOSL) as a successor of the World Ontology Specification Language (WOSL), as a first-order logic language for specifying the *state space and transition space* of a world. Peano Russel Notation (PRN) and some form of structured English is used, of which the syntax is defined in Extended Backus-Naur Form (EBNF). Figure 1: provides a graphical representation of GOSL as a *meta meta model of state space and transition space* of describing a world in general. Dietz & Mulder (2020, p.40) state that they adopt both the world ontology (*statics*) and system ontology (*dynamics*) as fundamentals in conceptualizing about the enterprise.

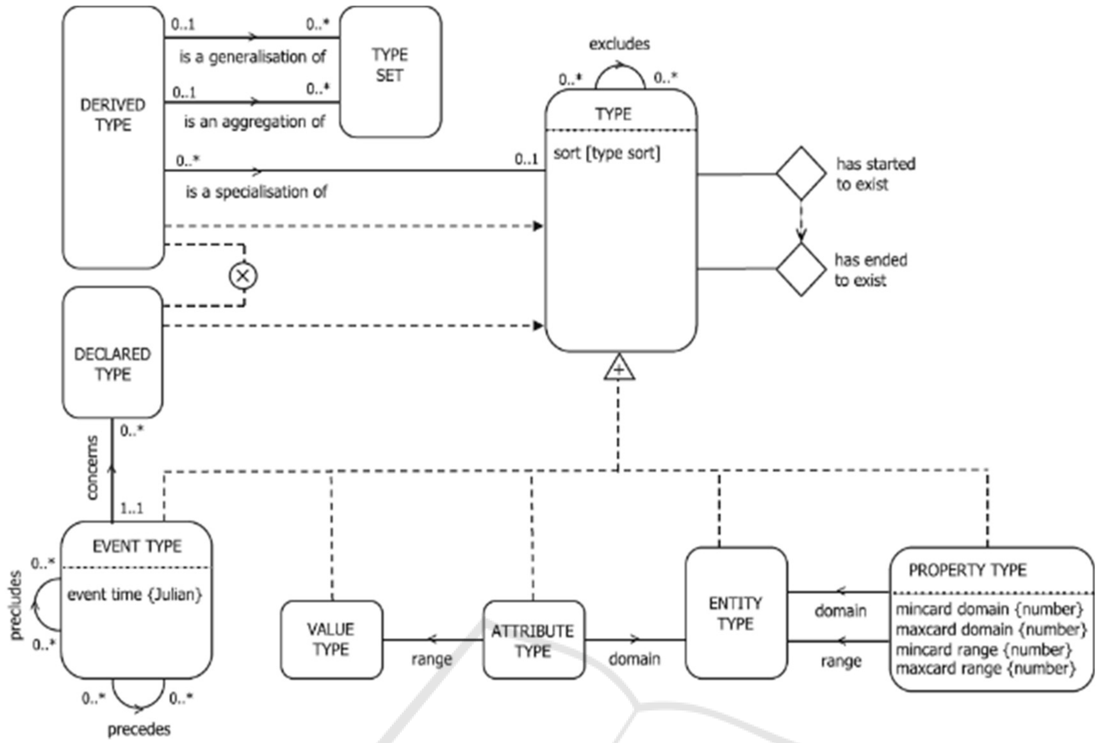


Figure 1: The Meta Meta Model of State Space and Transition Space.

2.2 Using Design Science Research

Previous work already applied a design science research methodology (DSRM), guided by Peffers et al. (2018) to develop the *meta model for enterprise systems dynamics* (MMESD) as an artefact (De Vries & Dietz, n.d.), instantiating concepts from the *meta meta model of state space and transition space*, shown in Figure 1: , and using GOSL's graphical and textual formalism.

The MMESD consists of a number of entity types that represent the world of enterprise systems dynamics (see Figure 4). The main entity types of the MMESD include the FACET (also called VARIABLE) type that has subtypes QUANTITY, INTERVENTION, REALITY ASPECT and PERFORMANCE AREA (PA) ASPECT. Some types may not be quantifiable, such as INTERVENTION, i.e. it cannot be a specialisation of QUANTITY. Furthermore, any FACET may be connected to LINK instances. A STOCK may also be connected to FLOW instances. A FEEDBACK LOOP includes a set of LINK instances as well as a set of FLOW instances. When one or more FLOW instances connected to an unrestricted ENVIRONMENT (AS SINK or SOURCE), an OPEN SYSTEM exists. Later in the article, we present all of the MMESD types, together with their extensions, in Figure 4. For the remainder of this article, we use the capitalised words to refer to the entity types.

The MMESD types can be instantiated as an enterprise systems dynamics model (ESDM), whereas the ESDM could be expressed using a *causal loop diagram* (CLD), a *stock and flow diagram* (SFD), or a combined *causal loop stock and flow diagram* (CLSFD). The MMESD would be a near-complete representation if any ESDM can be instantiated from the MMESD types.

Since the MMESD, represented via GOSL's graphical formalism (in Figure 4) and textual formalism (fully detailed in De Vries & Dietz (n.d.)), was only demonstrated via a single case, using Vensim, additional evaluation was required to ensure that the MMESD provides a comprehensive representation of at least SD concepts and some EE concepts. Validating the completeness of MMESD, the next section extracts conceptual knowledge from five of the common SD software tools according to the System Dynamics Society (n.d.): STELLA/iThink (High Performance Systems, 2003), AnyLogic (Grigoryev, 2021), PowerSim (Jensen, n.d.), Vensim (Ventata Systems, n.d.) and NetLogo (Wilensky, 1999). In section 0, we summarise the extensions to the original MMESD in a graphical form.

3 CONCEPT EXTRACTION FROM SOFTWARE TOOLS

This section highlights the differences in the use of symbols in the five software tools, to represent MMESD types graphically. We highlight two areas of concern.

(1) *An identification of new types*, that are not included in the current MMESD, such as the diamond symbol, used in STELLA, but it is not an instantiation of an existing MMESD type.

(2) *Different symbols for the same type.* The comparative evaluation illustrates the deviation in symbols that are used for the MMESD types QUANTITY, STOCK, and LINK, as detailed in Table. The lack of consistency in the symbols used for the concepts unfortunately creates ambiguity within the SD community. Further ambiguity is also created when the same tool allows for different symbols that represent the same concept. For instance, for CLDs Vensim allows the user to illustrate the polarity of the LINKs as "s" and "o" symbols rather than the conventionally-used "+" or "-" symbols (Sterman, 2000, p 141).

3.1 Use of the Diamond Symbol

The modelling packages use the diamond shape for different concepts as shown in Table. It represents a DECISION LOGIC instance in STELLA/iThink, an AUXILIARY instance in PowerSim, and a QUANTITY instance in NetLogo.

STELLA/iThink (ISEE, n.d.) is a well-known modelling program with a long history. It was founded in 1985 and has established itself as a mature modelling software. ISEE systems continually develops the software based on user feedback and requests, as a result it offers more concepts than other packages. One of these concepts is represented by a *decision process diamond* (DPD), incorporated in STELLA from version 7.0 onwards (McDonagh, Visser, Meller, Shaffer, & Prisley, 2002). A DPD represents an aggregation which simplifies the overall model structure without losing the necessary complexity of the model. The DPD is illustrated in Figure 2 by two examples.

In Figure 2, example (1), adapted from McDonagh et al. (2002), presents a DPD, labelled "Algae growth Factors", linked with a dotted arrow-line to "Biomass feedstock (Algae)", indicating feedback from the "Biomass feedstock (Algae)" STOCK instance. The information received allows a decision to be made that controls the FLOW RATE instance, labelled "Algae growth Rate". The DPD represented as "Algae growth Factors" can include multiple entities such as light intensity, and water content of soil.

In Figure 2, example (2), similar to Tulinayo et al.'s (2013) example, a DPD represents the decision logic "Manuscript reviewing process" after an academic article has been submitted for publication. Multiple activities have been condensed into the DPD, such as the editorial assessment and the peer review process.

The DPD element is recognised as an opportunity for modelers to simplify exiting models through aggregation, while also introducing discrete event simulation features.

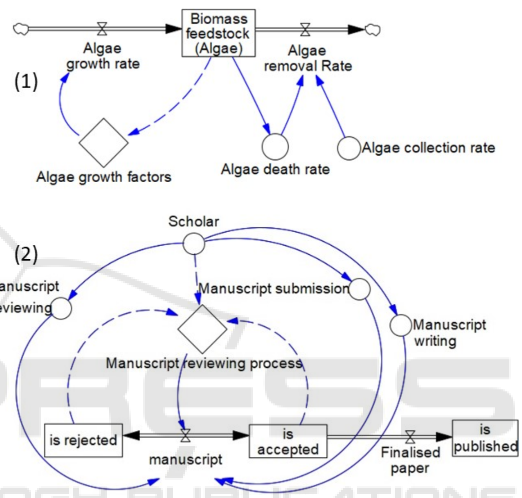


Figure 2: Examples of DPD: (1) the effect of Growth Factors on the Growth Rate of Biomass adapted from McDonagh et al. (2002) and (2) The reviewing decision process for a paper submitted for publication, similar to Tulinayo et al. (2013).

In NetLogo, the *diamond shape* is used to represent all QUANTITY instances, whereas in PowerSim, it is exclusively used for AUXILIARY instances.

The disparities in the use of the diamond symbol within NetLogo and STELLA merely add to the ambiguity within SD. We recognise that the process decision-making logic is a concept that was omitted in the initial version of the MMESD and hence Figure 4 highlights a new type, named DECISION LOGIC.

3.2 Link Symbolic Anomalies

A connector is a link in the model that carries information or influence from one FACET instance to the other (Ford, 2019). STELLA/iThink offers two types of LINKs. One is an action LINK that we re-labelled a *response* LINK to reduce confusion, the other is an *information* LINK. Figure 2 presents two examples of their usage. The *information* LINK instance represented by a dashed line, carries information to the DPD labelled "Growth Factor", which is used to arrive at a decision. The *response* LINK instance, represented by a solid line, shown as an outgoing line from the DPD labelled "Growth Factor", represents a response, i.e. a direct action resulting from the decision made. The combined use of the two LINK subtypes, together with the DPD, offered by STELLA/iThink, helps users to represent and visualise the decision-making process.

The solid line and dotted line have yet *different* interpretations within AnyLogic, i.e. using all LINK instances as *dependency* LINKs (Anylogic, n.d.) as shown in Figure 3, where the indicated FACET instances, e.g. "Total paying customers" are all quantifiable and hence they are all QUANTITY instances. In Figure 3 (1), a solid line is used from a QUANTITY instance to a FLOW RATE instance, when the value of the linked QUANTITY instance has been mentioned in the formula of the FLOW RATE instance. In Figure 3 (2), a dotted line is used when the value of the linked QUANTITY instance is mentioned as an initial value of the STOCK instance.

3.3 Stock Symbolic Anomalies

With the exception of STELLA/iThink, the software tools provide a generic representation for STOCK instances, as shown in Table. The subtypes of the STOCK type namely RESERVOIR, CONVEYOR, QUEUE and OVEN have been incorporated in the software to accommodate users within a material-flow setting. Tulinayo et al. (2013) elaborate that the

STOCK instance labelled "is accepted" in Figure 2, can be better represented as a CONVEYOR, while the STOCK instance labelled "is published" should remain a RESERVOIR, for the reason that any manuscript that "is accepted" for publication will be in a condition of waiting until it is published.

Table highlights MMESD concepts where different graphical representation are used within SD software tools, as well as new concepts that were omitted in the initial version of the MMESD.

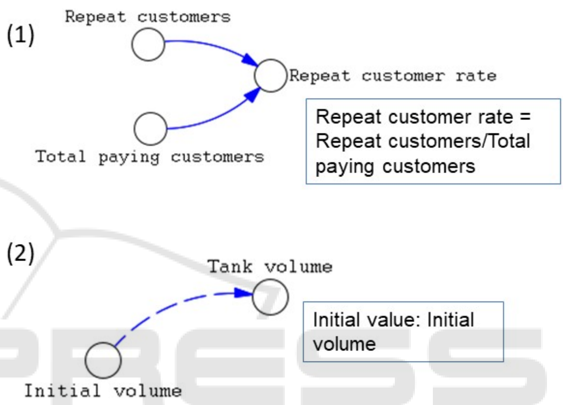


Figure 3: Dependency LINKs.

Table 1: MMESD type related to symbol.

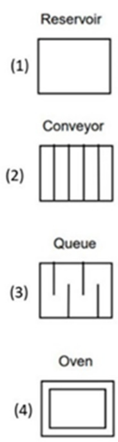
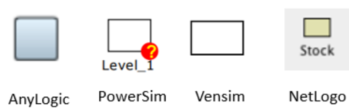
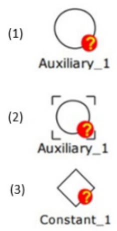
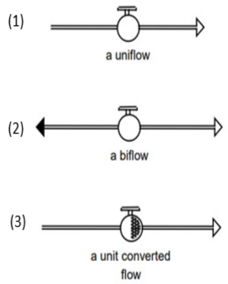
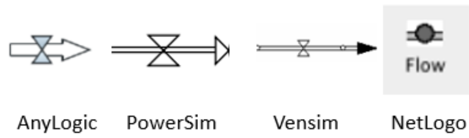
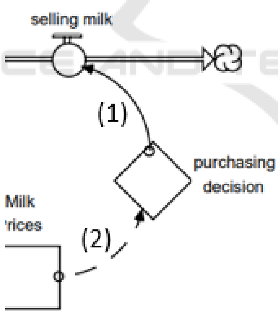
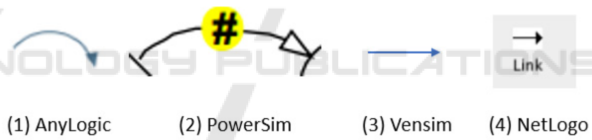
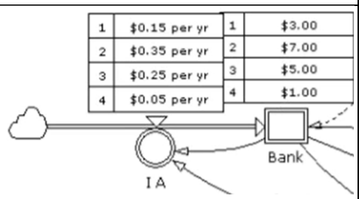
Type	STELLA/iThink		AnyLogic, PowerSim, Vensim, NetLogo
STOCK		(1) RESERVOIR is the most common subtype of STOCK and refers to the net flow, i.e., what has "flowed into", subtracted by what has "flowed out" of the RESERVOIR instance. It can never have a negative value. (2) CONVEYOR retains batch size and arrival integrity. The conveyor is unavailable until the quantity arriving first on the conveyor has passed its transit time and left the conveyor. (3) QUEUE and (4) OVEN are used for discrete event simulation. Queues develop when the flow is greater than the capacity to process. Similarly, OVENs can only process what has arrived if they are available and done "baking". High Performance Systems (2003) warn against the use of items (2), (3) and (4).	 AnyLogic represents a STOCK instance as a rectangle with rounded corners. PowerSim, Vensim, and NetLogo all represent a STOCK instance as a rectangle with sharp corners. **In MMESD:** An attribute was added, namely a "stock indicator", as shown in Figure 4 in red.

Table 1: MMESD type related to symbol. (cont.)

Type	STELLA/iThink	AnyLogic	PowerSim	Vensim	NetLogo
QUAN-TITY and some of its sub-types	 Circle symbol is used to represent some subtypes that exist in MMESD: (1) AUXILIARY, for algebraic operations (e.g. summation) (2) FLOW RATE (3) STOCK (4) PARAMETER (AS INPUT)	 Circle symbol is used to represent an AUX-ILIARY instance.	 (1) AUXILIARY instance with calculated value (2) AUXILIARY as shortcut is shown as a circle inside an incomplete square. (3) PARA-METER that remains constant in value is represented as a diamond.	AUX-ILIARY instances are represented as standalone text with no shape or border.	 Any QUAN-TITY subtype is represented by a diamond, and requires a unique name and expression.

Type	STELLA/iThink	AnyLogic, PowerSim, Vensim, NetLogo
FLOW and FLOW RATE	 (1) UNIFLOW only flows in the direction depicted by the arrowhead. (2) BIFLOW allows flow in both directions. (3) UNIT CONVERSION converts the units of measure while it flows.	 In AnyLogic, PowerSim, Vensim, and NetLogo FLOW RATE is depicted using an arrow with the arrowhead showing the direction of flow. In Vensim one way and two way flow can both be represented. **In MMESD:** An attribute was added, namely a “flow indicator”, to FLOW RATE as shown in Figure 4 in red.

Type	STELLA/iThink	AnyLogic, PowerSim, Vensim, NetLogo
LINK	 (1) RESPONSE represented by a solid line induces an action to the connected DECISION LOGIC instance. (2) INFORMATION represented by a dashed line, transmits information.	 (1) QUANTITY DEPENDENCY exists, where a solid line is used from a QUANTITY instance to a FLOW RATE instance, when the value of the linked QUANTITY instance has been mentioned in the formula of the FLOW RATE instance. INITIAL VALUE DEPENDENCY exists, where a dotted line is used when the value of the linked QUANTITY instance is mentioned as an *initial value* of the STOCK instance. (2), (3), and (4) The solid line represents an INFORMATION LINK to represent the connection or relationship between QUANTITY instances. **In MMESD:** An attribute was added, namely a “link indicator”, as shown in Figure 4 in red.
DECISION LOGIC (added to the MMESD)	The diamond shape represents a DECISION LOGIC instance, as shown in the image above.	The concept of DECISION LOGIC does not exist. **In MMESD:** Since DECISION LOGIC is not quantifiable, it can be classified as a subtype of FACET, as shown in Figure 4 in red.
[quantity] contains [set of quantity] (added to the MMESD)		Only PowerSim includes the concept of “array”, represented by a double-border graphical construct to represent. The interpretation of the double-border is that multiple QUANTITY instances exist, but for model simplicity they are shown with a single graphical construct. **In MMESD:** The relationship in Figure 4 in red, “[quantity] contains [set of quantity]” include cardinalities so that a QUANTITY instance has zero to many (0..*) QUANTITY instances in the array, whereas an array, i.e. a [set of quantity], exists for only one instance (1..1) of a QUANTITY instance.

4 EXTENDING THE MMESD

The MMESD extensions are shown in red in Figure 4, based on a comparison of existing SD software tools and the concepts that were extracted from the software tools. Extensions regard multiple existing entity types, including the LINK type, FLOW type and STOCK type. Furthermore, a new entity type, DECISION LOGIC was added as a subtype of FACET.

Not all of the types are included as graphical constructs on a CLSFD, such as VALUE PER TIME STEP (shaded in grey in Figure 4) and its specialisations, DERIVED VALUE and TIME STEP. The demonstration example in the following section could therefore not elaborate on these.

5 MMESD DEMONSTRATION

To support the decision-making process at teacher education faculties in Croatia, Tomljenovic et al. (2022) used SD techniques, creating a CLD and a SFD to run simulations. They modelled the flow of the population from high school (HS) graduates to teachers with a diploma, using AnyLogic. The model's objective is to help provide human resource (HR) management with a valid number of quotas for student enrolment.

Using Vensim, the MMESD concepts and their extensions, as shown in red in Figure 4, were applied to the teacher faculty case, re-modelled in Figure 5.

Due to the simplicity of the case, not all of the MMESD types were instantiated in the teacher faculty case, as indicated in section 6. Applying the MMESD guidelines on classifying a FEEDBACK LOOP instance as balancing or reinforcing, we identified three errors regarding three balancing loops in Tomljenovic et al. (2022) that we already corrected in our Vensim representation of the teacher faculty (TF) case by adding INTERVENTION instance "marketing TF studies", PA QUANTITY instance "number of bursaries offered", and a positive polarity to the LINK instance "perceived attractiveness of study.

Table provides a brief definition of the MMESD types followed by an instantiation from the demonstration case in Figure 5. Additional graphical representations used in Figure 5 (i.e., thick grey border for a conveyor) was introduced for visual distinction of new MMESD concepts on the CLSFD to reduce any ambiguity for the reader. As indicated in this article, existing modelling software differ in their ability to distinguish between all of the MMESD types.

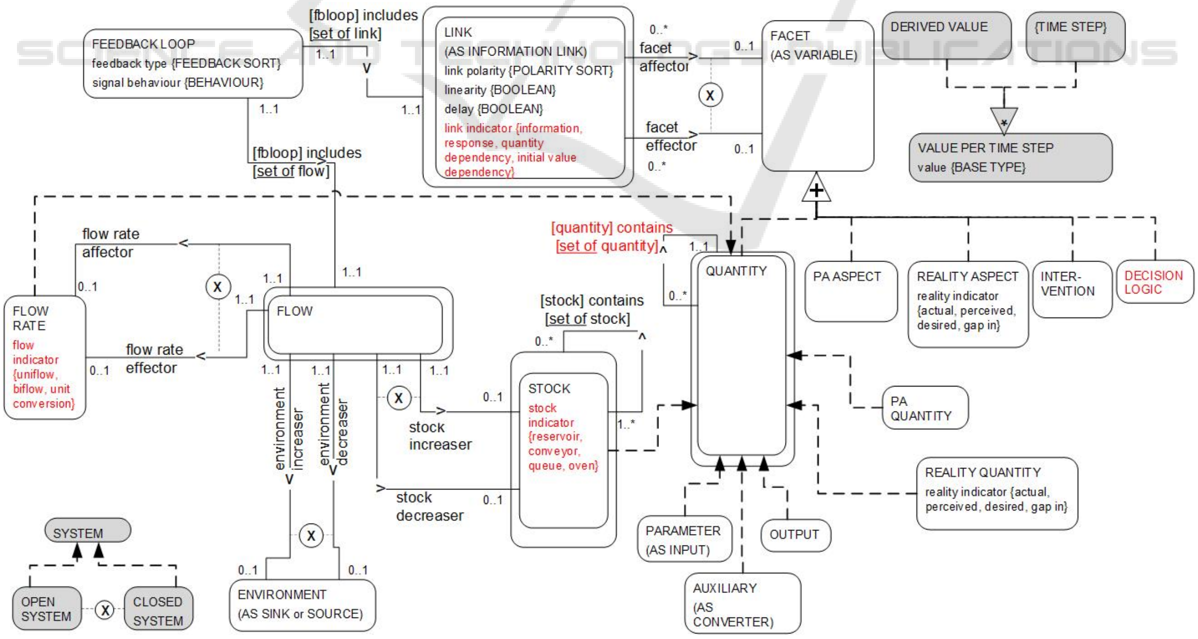


Figure 4: Extensions to the MMESD, Indicated in Red.

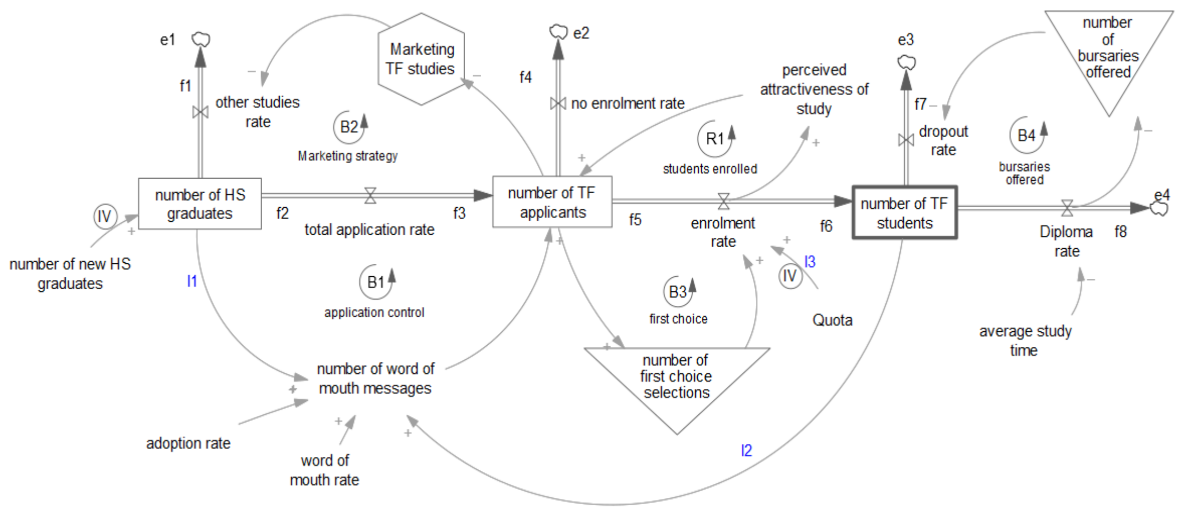


Figure 5: Extended MMESD Applied to Existing Teacher Faculty Case (Tomljenović et al., 2022) using Vensim.

Table 2: Extended MMESD Type Related to Figure 5.

Types	**Type definition and instantiation**
FACET (AS VARIABLE)	*entity type* facet **exists** FACET *is a generalisation of* QUANTITY, PERFORMANCE AREA (PA) ASPECT, REALITY ASPECT, INTERVENTION.
Figure 5	Instantiation examples are given for the subtypes of FACET.
QUANTITY	*entity type* quantity **exists** QUANTITY *is a generalisation of* FLOW RATE, STOCK, PARAMETER, AUXILIARY, OUTPUT, REALITY QUANTITY, PA QUANTITY
Figure 5	*quantity* number of new HS graduates **exists** *quantity* number of TF applicants **exists** **Further explanation**: The sub-types for QUANTITY have been renamed to appropriate labels to quantise the instance, so that its value can increase or decrease over time.
STOCK	*entity type* stock **exists** STOCK *is a specialisation of* QUANTITY
stock indicator	**the** *domain* **of** stock indicator **is** stock **the** *range* **of** stock indicator **is** ⌊reservoir, conveyor, oven, queue⌋
Figure 5	*stock* number of HS graduates **exists** *stock* number of TF applicants **exists** *stock* number of TF students **exists** **the** *stock indicator* **of** *stock* number of TF students **is** conveyor **Further explanation to the MMESD extension applied**: For the [stock] instance "number of TF students", any student enrolled at the faculty, remains a student for some period of time followed by the student exiting with their studies completed (via [flow rate] instance "diploma rate"), or exiting with their studies incomplete (via [flow rate] instance "dropout rate". Therefore, "number of TF students" can be represented as a conveyor, represented by a thick grey outline.

Table 2: Extended MMESD Type Related to Figure 5.(cont.)

Types	**Type definition and instantiation**
FLOW RATE Flow indicator **Figure 5**	*entity type* flow rate **exists** FLOW RATE *is a specialisation of* QUANTITY **the** *domain* **of** flow indicator **is** flow rate **the** *range* **of** flow indicator **is** {uniflow, biflow, unit conversion} *rate* total application rate **exists** *rate* enrolment rate **exists** **the** *flow indicator* **of** *flow rate* total application rate **is** uniflow **Further explanation to the MMESD extension applied**: The [flow rate] instance "total application rate" subtracts from [stock] instance "number of HS graduates" and adds to [stock] instance "number of TF applicants", indicating a one-directional flow, i.e. a uniflow.
FLOW stock increaser stock decreaser flow rate affector flow rate effector **Figure 5**	*entity type* flow **exists** **the** *domain* **of** stock increaser **is** flow; **the** *range* **of** stock increaser **is** stock **the** *domain* **of** stock decreaser **is** flow; **the** *range* **of** stock decreaser **is** stock **the** *domain* **of** flow rate affector **is** flow; **the** *range* **of** flow rate affector **is** flow rate **the** *domain* **of** flow rate effector **is** flow; **the** *range* **of** flow rate effector **is** flow rate *flow* f1 **exists;** *flow* f2 **exists;** *flow* f3 **exists;** *flow* f4 **exists** **Further explanation to the MMESD extension applied**: **the** *stock increaser* **of** *stock* number of TF applicants **is** f3 **the** *stock decreaser* **of** *stock* number of HS graduates **is** f1 **the** *flow rate affector* **of** *flow* f2 **is** total application rate **the** *flow rate effector* **of** *flow* f3 **is** total application rate
ENVIRON-MENT environment increaser environment decreaser **Figure 5**	*entity type* environment **exists** **the** *domain* **of** environment increaser **is** flow **the** *range* **of** environment increaser **is** environment **the** *domain* **of** environment decreaser **is** flow **the** *range* **of** environment decreaser **is** environment *Environment* e1 **exists** **the** *environment increaser* **of** *environment* e1 **is** *flow* f1 **Further explanation:** There is only an instantiation of environment increaser, no environment decreaser.
PARAMETER **Figure 5**	*entity type* parameter **exists** PARAMETER *is a specialisation of* QUANTITY *parameter* number of new HS graduates **exists**
PA QUANTITY **Figure 5**	*entity type* pa quantity **exists** PA QUANTITY *is a specialization of* QUANTITY *pa quantity* number of first choice selections **exists** (indicated graphically with an inverted triangle) *pa quantity* number of bursaries offered **exists** **Further explanation:** number of first choice selections is quantifiable, and Tomljenovic et al. (2022) identify it as a key indicator (performance area) for human resource decision makers to help identify how many students are interested in the teacher faculty.
INTERVEN-TION **Figure 5**	*entity type* intervention **exists** INTERVENTION *is a subtype of* FACET *intervention* marketing TF studies **exists**
AUXILIARY **Figure 5**	*entity type* auxiliary **exists** AUXILIARY *is a specialisation of* QUANTITY *auxiliary* number of first choice selections **exists**

Table 2: Extended MMESD Type Related to Figure 5. (cont.)

<table>
<tr><th>Types</th><th>Type definition and instantiation</th></tr>
<tr><td>LINK
link indicator

facet affector
facet effector
link polarity</td><td>entity type link exists
the domain of link indicator is link
the range of link indicator is ├information, response, quantity dependency, initial value dependency┤
the domain of facet affector is link; the range of facet affector is facet
the domain of facet effector is link; the range of facet effector is facet
the domain of link polarity is link; the range of link polarity is polarity sort; i.e. ├positive, negative┤</td></tr>
<tr><td>delay</td><td>the domain of delay is link; the range of delay is Boolean, i.e. ├true, false┤, with default “true”.</td></tr>
<tr><td>linearity

Figure 5</td><td>the domain of linearity is link; the range of linearity is Boolean, i.e. ├true, false┤, with default “true”.
link l1 exists; link l2 exists; link l3 exists
the range of link indicator l3 is initial value dependency (circular shape labelled “IV”)
Further explanation of MMESD extension: The remaining links are all quantity dependency links. However, to demonstrate an alternative representation of the case Figure 6 has been included, demonstrating other range values, i.e. information, and response.
The affector of link l1 is number of HS graduates
the effector of link l1 is number of word of mouth messages
the link polarity of link l1 is positive
the delay of link l2 is true
meaning: As indicated by De Vries & Dietz (n.d.), a link automatically implies a delay and no additional visual cues are required.
the linearity of link l3 is true <not shown explicitly>.</td></tr>
<tr><td>FEEDBACK LOOP
feedback type

behaviour

Figure 5</td><td>entity type feedback loop exists

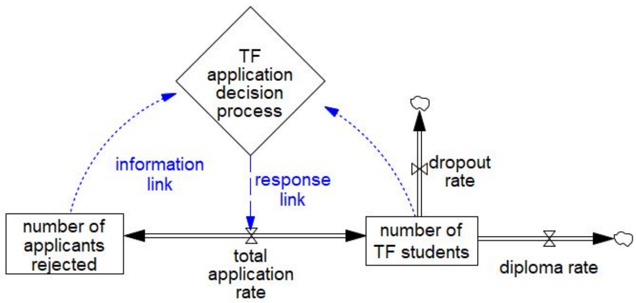
the domain of feedback type is feedback loop
the range of feedback type is feedback sort, i.e. ├reinforcing, balancing┤.
the domain of signal behaviour is feedback loop
the range of behaviour is behaviour
the feedback type of feedback loop B1 is balancing
the behaviour of feedback loop is application control</td></tr>
<tr><td>DECISION LOGIC
Figure 6</td><td>entity type decision logic exists
DECISION LOGIC is a specialisation of FACET


Figure 6: A demonstration of the DPD applied to the teacher faculty case.
Explanation: Information about the “number of applicants rejected” and the “number of TF students” is used by the faculty to make a decision during the teacher faculty application decision process. The response link leads to an action on the total application rate, affecting the back-flow of applicants rejected compared to the forward flow of applicants accepted.</td></tr>
</table>

6 DISCUSSIONS AND CONCLUSIONS

The article emphasised the need for a MMESD to consolidate the emerging concepts within SD. We used five prominent SD software modelling tools to highlight an extension of the existing MMESD, accommodating the new concepts that are evident in the software tools. Since the initial version of MMESD required further evaluation, and we wanted to include some of the newly-identified extensions to the MMESD, we used the teacher faculty case to construct a CLSFD in Vensim, providing an additional demonstration of the MMESD by instantiating some of the MMESD types. A limitation of the study is that the teacher faculty case is fairly simple, facilitating ease of understanding, but we could not demonstrate the types PA ASPECT, REALITY QUANTITY, REALITY ASPECT, OUTPUT and the recursive connection "[quantity] contains [set of quantity]".

The teacher faculty case highlighted the need for more case studies to help readers apply MMESD concepts. Future work should obtain further evidence on whether the MMESD is useful to differentiate between concepts to construct high-quality CLSFDs.

Sterman (2000) supports participative modelling, rather than an analyst modelling in isolation. A new trend in modelling is to work participatively. This article focused on tooling that supports simulation capability. If the intention is to obtain inputs from stakeholders in a collaborative way, future work on participative modelling, using such tools, would add value. A few examples include Loopy (Loopy, n.d.), Edraw (EDraw, n.d.), and Plectica (Cabrera & Cabrera, 2018).

Future work can also refine the MMESD by comparing a larger set of software tools. According to the System Dynamics Society (n.d.) the following software tools are also commonly used: Dynaplan, GoldSim, Berkley Madonna, Simile, Simgua, TRUE, and Simscision. The MMESD may also be further validated using more complex cases.

The MMESD was expressed using the graphical and textual formalism of GOSL, contributing an additional example of specifying a meta model, based on the *meta meta model of state space and transition space* and GOSL. For future work, we suggest additional experimentation with GOSL, i.e. where different conceptual modellers independently abstract from an existing model to create a meta model, expressed in GOSL, inspecting the similarity of their resulting meta models.

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