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Decision Support

A toolkit of designs for mixing Discrete Event Simulation and System Dynamics

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ABSTRACT

In recent years there has been significant interest in multimethodology and the mixing of OR/MS methods, including Discrete Event Simulation (DES) with System Dynamics (SD). Several examples of mixing DES and SD are described in the literature but there is no overarching framework which characterises the spectrum of options available to modellers. This paper draws on a sample of published case studies, in conjunction with the theoretical literature on mixing methods, to propose a toolkit of designs for mixing DES and SD which can be implemented as a set of questions which a modeller should ask in order to guide the choice of design and inform the associated project methodology. The impetus for this work was the perceived need to transfer insight from reported practice in order to formalise how the two methods can be and have been mixed.

1. Introduction

Multimethodology and the mixing of OR/MS methods continue to be of interest to the OR/MS community (Howick & Ackermann, 2011), with increasing attention to the application of a mix of simulation methods (Pidd, 2012). This paper focuses on mixing DES and SD, a combination which is increasingly often reported in the literature and several position papers which support this mix exist (Brailsford, Desai, & Viana, 2010; Lane, 2000; Pidd, 2012). However, how DES and SD can be and have been mixed is not well defined. Software tools are available offering the functionality of both methods within a single environment, [1] but there are multiple ways of mixing the methods and the most appropriate will depend on the context. Therefore there remains a need to collate and expand existing frameworks to develop *"a conceptual philosophy and practical methodology for combining SD and DES in a real context"* (Viana, Brailsford, Harindra, & Harper, 2014, p. 197) enabling modellers to better understand how DES and SD can be mixed and thereby inform practice. This paper reviews the literature relating to mixing DES and SD in theory and practice in order to propose a toolkit of mixed methods designs for mixing DES and SD and to inform the associated project methodology. The research described was conducted to inform, and was reflected upon throughout, an action research project in collaboration with the Beatson Oncology Centre, Glasgow (detailed in Morgan, Belton, & Howick, in press).

Although all modelling projects are unique, reviewing the literature to find points of commonality enables a researcher to make connections between ideas, theories and experiences (Hart 1998) and ultimately to pass on understanding. General reviews and classifications of mixing methods within OR/MS modelling exist, but papers with a DES and SD focus are context specific. There is currently not an overarching framework that covers: the spectrum of options available to a modeller (taking a broader OR/MS mixed methods approach), the technical details which need to be considered when mixing these methods, and the importance of project context. Such a generic framework should provide insight into the philosophical, methodological and technical considerations when using each method within a mixed method design. The development of appropriate software might also alleviate some of the barriers to mixing methods, but this is outside the scope of this paper. However, whilst some multi-method software provides an environment within which to build a conceptualised mixed model, it is important to be aware that if a modeller does not have clear paradigm and conceptual guidance this may lead to an inappropriate or over-complex model.

In addition to the availability of software, there is a need to support modellers interested in mixing OR/MS methods by asking what method should be used when (Flood & Jackson, 1991). This

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[1] Examples include: Aivika (hackage.haskell.org/package/aivika-0.1), AnyLogic (www.xjtek.com/AnyLogic), GoldSim (www.goldsim.com).

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paper takes frameworks from the wider OR/MS mixed methods literature and seeks to adapt them to the simulation context, drawing on a number of published projects which mix DES and SD, in order to present a toolkit of designs that have been shown to work in practice and have overcome concerns of paradigm compatibility.

The next section presents the background to this research, comparing DES and SD to highlight the differences, commonality and complementarity of the methods and summarising interest in mixing OR/MS methods. Section 3 describes the preliminary mixed methods designs collated through analysis of the mixed methods literature. Section 4 examines a number of mixed DES and SD projects selected from the literature and considers their implications for the mixed method designs described in Section 3. The paper concludes by proposing a toolkit of mixed method designs and discussion of the implications for and on methodology selection in practice.

2. Background

This paper adopts a similar view to Howick and Ackerman (2011) in that the aim is to examine the literature for *"all forms of mixing methods"* (p. 504), and considers the spectrum of how DES and SD can be and have been mixed. The term mixing methods is used in this paper to describe the combined use of more than one technique, tool, method, methodology or paradigm. The term method will be utilised to describe both DES and SD; reflecting a general descriptor of OR/MS methods, tools and techniques. Methodology, in this paper, will refer to the overall structure of the intervention which may consist of a mixed methods design. This approach reflects Mingers and Brocklesby's (1997) definition that a methodology describes 'what type of activities should be undertaken' and the method is the 'how'. Paradigm will refer to the theoretical perspective, the philosophical context grounding the method logic (Crotty, 1998).

2.1. Comparison of DES and SD

2.1.1. System Dynamics

SD is a form of continuous simulation modelling that may be characterised by its ability to represent feedback in systems (Forrester, 1958). SD models the average flow of the system rather than individual events, explicitly representing delays and feedback experienced within a system to discover underlying principles and behaviour over time. The efficacy of SD is based on its ability to capture the whole system rather than focusing on short term goals and single measures of performance, which can lead to inappropriate conclusions (Taylor & Dangerfield, 2005). SD models are, in general, a macroscopic view of a system, which may be used to explore how the system structure impacts the system behaviour.

2.1.2. Discrete Event Simulation

DES is a method in which the dynamics of the system are triggered by events, allowing users to model the individual events experienced within a system. DES enables the user to explore progression through a system (Pidd, 2004) and is often used to represent systems at an operational level, where the individual interactions and the variation of experience of system entities over time is important. The variability inherent in everyday life can be captured and the multiplicative effect of stochastic elements can be observed, but DES does not explicitly seek to model feedback.

2.1.3. Comparing methods

DES is one of the most popular OR/MS modelling methods and has been used with other OR/MS methods such as statistical analysis, data mining, problem structuring, process flow mapping, optimisation and multi criteria decision analysis (Robinson, 2005).

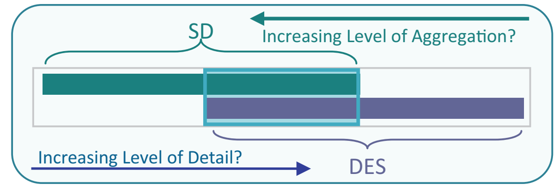

Fig. 1. The possible continuum of DES and SD.

Lane (1999) assures that SD is not restricted to one paradigm and may be mixed with other methods as Forrester's ideas operate at the 'method' level. Enabling modellers to "*see enough of the 'other' discipline to sense where future collaboration might be beneficial*" (Morecroft & Robinson, 2006, p. 11) may encourage modellers to become less anchored to their method of choice. Comparing the methods supports mixing by allowing modellers to view characteristics of both methods side-by-side, revealing the overlap and gaps.

There are numerous studies that consider both methods (for example: Chahal & Eldabi, 2008a,b; Tako & Robinson, 2010), with the focus recently on providing a more balanced and empirical comparison, which seeks to consider how mixing the methods could "*yield complementary* insights" (Morecroft & Robinson, 2006, p. 11). Pidd (2004) notes three perspectives which need to be coherent in order to select appropriate methods: the methodology, the problem and the system. Table 1 draws together comparative studies of DES and SD using these three perspectives. The methods are clearly distinguished by some characteristics (such as the extent to which stochasticity is modelled) and are more closely aligned on others (such as the need for good data). Other characteristics may overlap depending on how they are implemented (illustrated in Fig. 1 for the characteristic "level of detail incorporated in a model").

Despite the differences, Sweetser (1999, p. 8) noted that *"many problems could be modelled by either approach and produce results that would look very similar"*. However, method choice influences what is included and excluded from the model, which in turn affects the results (Davies, Roderick, & Raftery, 2003). When learning a method, a modeller learns to view a system in a certain way and this impacts their choice of method, hence proponents of either method may naturally tend towards its use but it can be informative to take a *"step back and assess which toolkit should be used"* (Chick, 2006, p. 22).

2.2. Mixing OR/MS methods

Real-world problem situations are often highly complex and it is possible to use different methods to focus on different aspects of a situation. Jackson and Keys (1984) suggest that the OR/MS community is motivated to mix methods by a desire to improve modelling capabilities and increase the effectiveness of modelling projects. All methods have their strengths, weaknesses, benefits and limitations; mixing methods offers the potential to overcome some of the shortfalls, providing an additional methodology to cope with wicked problems and systems.

In their 2002 survey Munro and Mingers found that mixing OR/MS methods happened because each method was *required*, and that methods were mixed in an adhoc/emergent manner. More recently Howick and Ackermann's (2011) review of papers, which describes mixing OR/MS methods in practice, revealed a number of reasons for mixing including: to deal with a complex problem system, to support stages of a project, to obtain specific benefits from specific methods and to overcome method shortfalls.

There are also some concerns relating to mixed methods. Concerns of paradigm incommensurability, which are discussed in

Table 1
Comparison of classic perspectives on DES and SD.

		SD	DES
Methodology	Philosophy	Method, a professional approach (Forrester, 1958) Well defined methodology	Method, tool or technique No single clear philosophy
	Entities	Continuous flows (Forrester, 1961), homogenised entities (Lane, 2000)	Individual Entities (Morecroft & Robinson, 2006)
	Stochastic vs. deterministic (Rawlings, 2000)	Low importance of stochastics	High importance of stochastics
	Model look & feel	Stocks, flows, delay structures (Sterman, 2000)	Network of queues and activities, resources (Pidd, 2004)
		Explicit representation of feedback (Morecroft & Robinson, 2006)	Implicit representation of feedback (Morecroft & Robinson, 2006)
	Relationships (Morecroft & Robinson, 2006)	Mainly non-linear	Mainly linear
	Data dependency (Taylor & Lane, 1998)	Data broadly drawn: combining all information available (including judgemental and informational)	Primarily tangible with some informational
	(Tako & Robinson, 2009)	Requires good quantitative data	Requires good quantitative data
System	Boundary (Sweetser, 1999)	Attempt to capture all elements (large boundary)	Focus on events that trigger changes to occur; narrower focus
	Detail (Pidd, 2004)	More macro level detail	High level of detail (Micro)
	(Mak 1992)	Measurable and informational flows	Physical, tangible, material measurable flows
	(Taylor & Lane, 1998)	Holistic, general systems	Analytic focus
	Aggregation (Morecroft & Robinson, 2006)	Aggregate events to rates, emergent behaviour	Event focus and individual decisions; state changes
Problem	Goal/Aim	Explore global structural dependencies (Morecroft & Sterman, 1994), yield a better understanding of social systems (Forrester, Mass, & Ryan, 1976)	Explicitly explore the impact of randomness and how the system might behave (Tako & Robinson, 2009)
		Examine dynamic complexity (as part of systems thinking) (Kim & Senge, 1994)	Examine detail complexity (Brailsford, 2008)
	Problem scope (Lane, 2000)	Strategic & Policy, system view, conceptual level	Operational & Logistical, process view

detail by many authors (Harwood, 2011; Jackson, 2011; Mingers, 2011; Mingers & Brocklesby, 1997; Mingers et al., 1997), highlight the necessity for modellers to carefully consider the paradigm implications of mixing methods to ensure that the application of individual methods is consistent with their theoretical assumptions (Eden, 1990). More recently Pidd (2012) describes mixing methods with simulation as "*no big deal*", and Brailsford, Churilov, and Dangerfield (2014) deem mixing methods possible and valuable but models must be fit for purpose. Despite discussion within the OR/MS community, guidance for mixing DES and SD in an applied context remains ill-defined (Viana et al., 2014).

2.3. Mixing DES and SD

As noted at the beginning of this paper, the literature highlights that mixing methods may be referred to in various ways using different descriptors. A literature search identified 36 papers from the OR/MS literature which described mixing DES and SD in practice (after examining title, abstract and keywords for the use of DES and SD, and reference to a real-life project). Thirty five of the papers discuss mixing methods undertaken in practice and one describes a situation in which a mixed method approach was reflected upon as a viable alternative approach at the end of a project. Table 2 summarises the terms used by the authors of each paper to describe the project methodology. 'Hybrid' modelling was the most popular term used. This term was first proposed in the context of mixing OR/MS methods by Shanthikumar (1983) to describe several mixed simulation and analytic model designs; it is used in a range of contexts, with a variety of meanings and is not restricted to the mixing of DES and SD. Overall, there is little consistency in the terms used, which will be explored further in the sections which follow.

This section has provided an overview of DES and SD; compared the methods, highlighting their complementarity but also how the application of a method may differ depending on the problem and system modelled; and summarised the interest in and concerns with mixing DES and SD. The next section collates theoretical frameworks, outlining the approach taken to identify the initial mixed method designs taken from the literature, and describes the research design.

3. A theoretical perspective on mixing methods

A conceptual framework should convey the key factors and concepts of a subject matter, identify relationships between them and form definitions (Miles, Huberman, & Saldana, 2014). Three key sources of mixed method designs were identified to develop a conceptual framework for mixing methods. These designs are generic for OR/MS methods, rather than DES and SD specific, and were selected as they are regularly referred to, or expanded on, by those seeking to add to the theory of mixing OR/MS methods.[2] This section describes and collates the three sources, identifying key characteristics which inform the specification of a new set of designs. The new designs and their characteristics are used to review the published examples of mixing DES and SD, leading to the proposal of a toolkit of mixed method designs for DES and SD.

3.1. Comparison, enrichment and integration

Bennett (1985) presents an early discussion of multimethodology, presenting the view that methods may focus on, emphasise or encapsulate differing aspects of a particular issue. Individually, each method has its strengths but also aspects that are captured less sufficiently. Mixing methods therefore hold the promise of an overall better approach. Three designs, which progressively provide a deeper mix of the methods, are proposed:

- *Comparison* suggests a lens with which to view two methods (exploring compatibility and complementarity) whilst

[2] Examples include: Bryant, Darwin, and Booth (2011), Franco and Lord (2011), Howick and Ackermann (2011), Keys (1997), Kotiadis and Mingers (2006), O'Brien (2011), Ormerod (1997), Robinson (2001), Zhu (2011).

Table 2
Papers discussing mixing DES and SD in the context of a specific modelling project.

Description of mixing methods	Papers
Both	Dierks, Dulac, and Leveson (2008)*, Martin and Raffo (2000), Su and Jin (2008)*
Combined	Chatha and Weston (2006), Djanatliev and German (2013), Lee, Cho, and Kim (2002)
Comparing or versus	Morecroft and Robinson (2006), Ozgun (2009)
Composite	Brailsford et al. (2010), Viana et al. (2014)
Hierarchical	Kouskouras and Georgiou (2007)
Hybrid	Alvanchi, Lee, and AbouRizk (2011), Barton (2000), Borshchev, Karpov, and Kharitonov (2002), Donzelli and Iazeolla (2001), Jacob, Suchan, and Ferstl (2010), Mazaeda, Merino, de Prada, and Acebes (2012), Pena-Mora, Han, Lee, and Park (2008), Pruckner and German (2013), Rabelo et al. (2007)
Hybrid & Integrated	Robledo, Sepulveda, and Archer (2013), Venkateswaran and Son (2005), Wang, Brême, and Moon (2014)
Hybrid & combined	Abduaziz, Cheng, Tahar, and Varma (2015), Zulkepli, Eldabi, and Mustafee (2013)
Integrate & Synchronise	Helal et al. (2007)
Integrated	Albrecht, Kleine, and Abele (2014), Brailsford, Churilov and Liew (2003)+, Reiner (2005)
Inclusion / addition	Phelps, Parsons, and Siprelle (2002)**
Discrete events in SD	Howick and Eden (2004), Wolstenholme and Coyle (1980)
"DES then SD"	Brailsford, Lattimer, Taranas, and Turnbull (2004)
"SD for DES"++	An and Jeng (2005)
"SD in DES"	Fioroni et al. (2007)
Mixed Discrete and Continuous	Béchard and Cote (2013)

Notes:
* Not described as mixed methods.
** Referred to by brand name: *Simulation Dynamics*.
\+ Mixing identified as a future direction.
\+\+ SD used first to help develop the DES.

maintaining paradigm integrity; a precursor to a more ambitious mix.
- *Enrichment* seeks to add value to a method using elements of another; nothing emerges that was not previously contained in any of the methods.
- *Integration* separates methods from their paradigm and uses elements of them to provide something new.

3.2. Sequential, parallel and interaction

Schultz and Hatch (1996) propose three designs: *sequential*, *parallel* and *interaction*. The first two designs refer to the order in which different methods are applied, maintaining the integrity of the paradigm boundaries. For example, within the sequential design, paradigms are viewed as "*mutually complementary*" (p. 533) by revealing sequential levels of understanding, with the relationship between paradigms as linear and unidirectional. *Sequential* and *Parallel* designs may be viewed as simple to implement mixed methods designs; possible precursors to an *Interaction* design which is a deeper, more complex mix of methods. The designs proposed by Schultz and Hatch (1996) pay careful attention to the paradigms and their boundaries, highlighting the need to consider the permeability of these boundaries to allow connections to be made between methods.

3.3. Isolationism to multimethodology

Mingers and Brocklesby (1997) discuss the overall spectrum of methodology selection, from a single method to fully combining two methods. *Isolationism* highlights basic single method selection and how it is often a choice: an 'or' rather than 'and'. *Selection* illustrates the assessment of methods that often forms an internal process of the modeller but does not inform the design of a mixed project specifically.[3] *Combination* implies the use of more than one method within a study but provides no insight into how this combination might occur. *Enhancement* is a design used to adjust a primary method with aspects of another allowing deeper insight, whereas *Multimethodology* involves partitioning methodologies in order to combine. These designs highlight the practical and technical considerations and demonstrate that a single method would be the end result.

3.4. A new set of mixed method designs

Not all of the designs considered are presented in the literature to the same level of detail, so they are not directly comparable, but there are clear points of commonality. The literature review in Section 2 noted three perspectives important to consider when evaluating methods: the system (input), the problem (output) and the methodology (process). These perspectives were used to compare and group the designs:

Input: what are the building blocks (the number of methods and paradigms)?
Process: how the methods are mixed (interactions and overlap)?
Output: what is the desired output, why is the project needed?

This led to a refined set of designs (Fig. 2) which are all applicable at the paradigm, methodology or technique level. Fig. 3, which acts as a key to Fig. 2, illustrates the hierarchy of a paradigm over a methodology, and subsequently over a method and a technique.

This section has presented the theoretical backdrop to developing a conceptual framework and practical set of designs for mixing DES and SD. The applicability of the identified mixed method designs is evaluated in the following section using a selection of examples from the literature.

4. Examples from the literature

Examples which satisfy the following three criteria were sought: explicitly describes the use of DES and SD, action research or case study design, details a mixed methods project. Selection was limited to papers published up to and including Dec 2012 and linked to the OR/MS field,[4] rather than those straddling other disciplines, as the language used and definitions of methods may differ. Of the 36 papers identified initially (Table 2), 13 journal articles

[3] No clear distinction was found between *Isolationism* and *Selection*.

[4] Simulation is used in a broad range of fields but this work focuses on mixing methods within the OR/MS field.

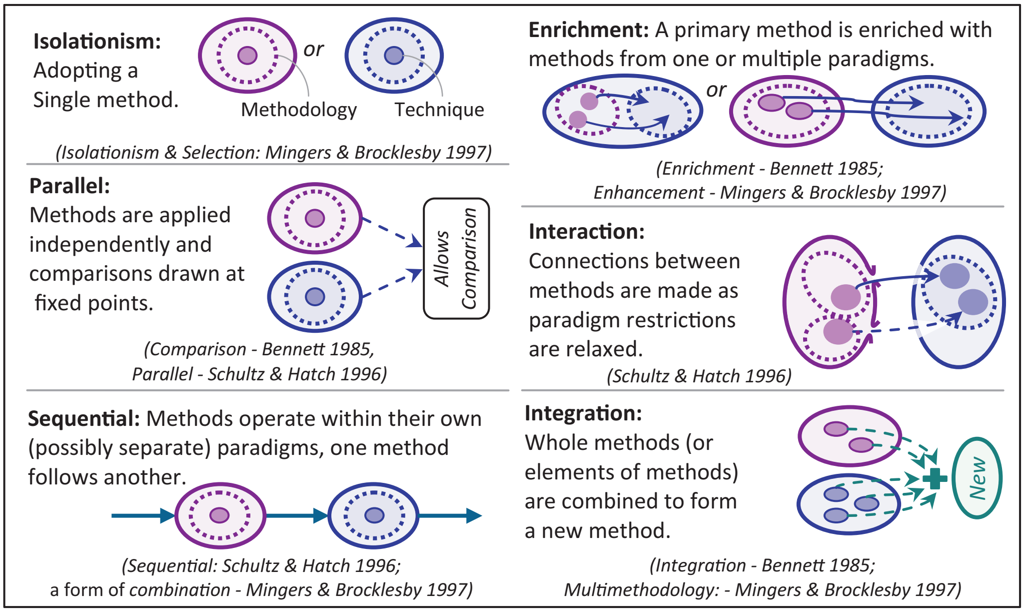

Fig. 2. Mixed method designs.

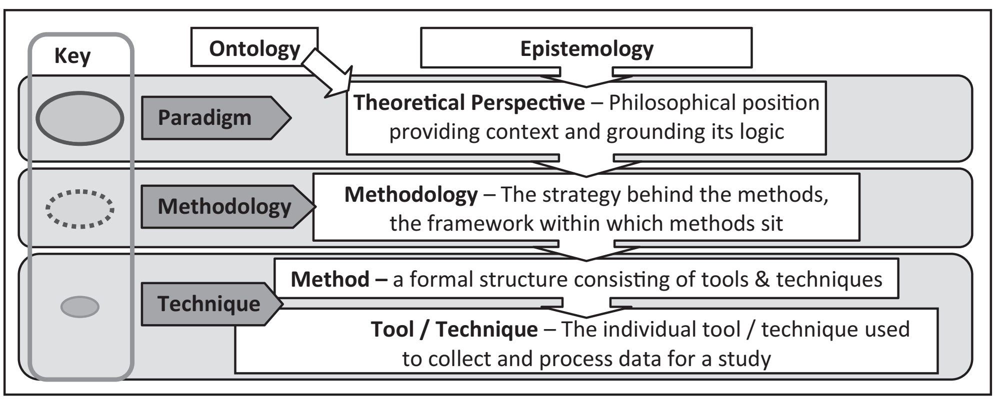

Fig. 3. Relationships between tools, methods, methodology and paradigm (based on Crotty, 1998, p. 7)—for use as a key to Fig. 2.

and peer reviewed conference proceedings were selected as examples as they contained sufficient detail and covered the spectrum of designs.

Howick and Ackermann's (2011) analysis of mixing OR methods in practice identified several distinguishing themes by which to summarise projects: modeller implications, form of mix, nature of intervention, client value and mix rationale. These are used alongside themes from the multimethodology literature (described in Section 3) to form the following features to review the examples:

1. **System modelling view** is the problem boundary taken by each method and the detail with which the associated system is modelled. This may be the key factor for initial method selection (the decision to use both DES and SD).
2. **Method dominance** is the emphasis placed on each method within the project.
3. **Mixed method design** is how the methods are used together; the order methods are used.
4. **Technical justification of mix** is the authors' reasons for choosing to mix the methods; how mixed methods enhanced the project outcome over and above a single method.

Papers were grouped according to the mixed method design they were identified to align with (given the definitions stated in Fig. 2). The above features provided a common basis for comparison, allowing differences in projects to be identified and additional features to emerge. The following section is structured as follows; one paper is used to illustrate each mixed method design, and comparative insights drawn from the remaining papers grouped as that design. Following this review, the appropriateness of the mixed method designs and the features are reflected upon to inform a toolkit of mixed method designs presented in Table 8.

4.1. Design 1: Parallel *use of DES and SD*

Morecroft and Robinson (2006) present a project that applies DES and SD (undertaken by two separate modellers) to the same problem for comparison. The aim of the project was to provide insight into the applicability of the two methods to model a fishery. It examines how DES and SD may be considered complementary when used in parallel, concluding that both have a role to play in developing understanding of the dynamics of fisheries.

System view: The methods are applied completely independently to provide insight into the same problematic area and form hypotheses about reasons for the observed behaviour. Both methods take an identical view of the overall problem situation, defining the same system boundary (illustrated in Fig. 4), aiming to capture the same model boundary and outputs by examining the level of fish stocks over time.

Table 3
Design of combination of Morecroft and Robinson (2006).

Mixed method design	*Parallel*—illustrated in Fig. 4
Level of interaction	*Zero*—comparisons drawn but no interaction between the models
Number of methods	*Two*—adopting the full paradigm / modelling philosophy of each
Level of overlap	*Zero*—methods remain distinct
Result of the mix	*Two*—independent complete models

Dominance: The methods were applied equally, with each receiving the full individual attention of a modeller specialising in that method. Both models were used to provide insight at three stages in the development process, revealing similarities and differences between the methods and their outputs.

Design: The methods had a common starting point and were applied independently and in parallel by experts in their respective modelling field. Table 3 summarises the design of combination.

Technical justification of mix: This project demonstrates how both models offer plausible explanations for behaviour, suggesting that each method can provide value and thus either may be useful within a specific context. The term parallel succinctly captures the design of the intervention, and all key factors of the methodology are able to be summarised. The benefit of using the two methods in this project was the complementary insight obtained from two different method representations of the same system: the value was in the difference of the methods.

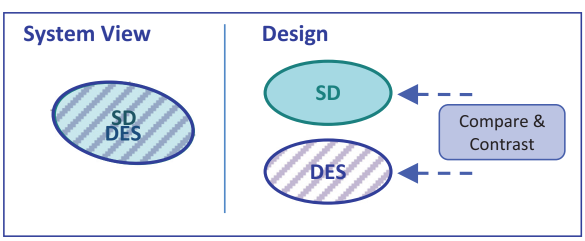

Fig. 4. Application of distinct SD & DES models in Morecroft and Robinson (2006).

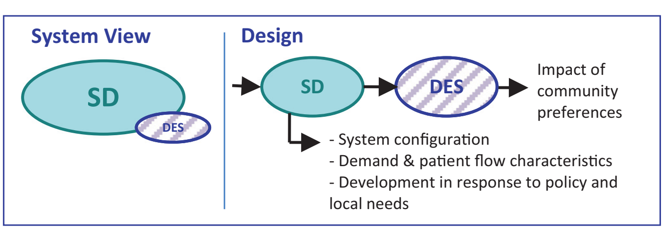

Fig. 5. Application of distinct SD then DES models in Brailsford et al. (2004).

4.2. Design 2: Sequential *DES and SD*

Brailsford, Lattimer, Taranas, and Turnbull (2004) discuss a project that may be described as the sequential mix of the methods: SD then DES. This case study was embarked upon as a SD project, but during the process a DES was deemed necessary. The two models are used in conjunction with each model fulfilling a unique purpose. This paper illustrates the case for using one method to identify the need for and to inform another method.

System view: The SD model was used to capture the whole problem system under study, whereas the DES model was rapidly developed to focus on a specific part of the system. The DES is therefore used to complement the SD model: to explore the same system but to focus on part of the system behaviour that is an area not fully captured in the SD model (illustrated in Fig. 5).

Dominance: The SD method was applied entirely, and then the DES was rapidly developed for further insight. The majority of the focus was on the SD model but this focus shifted once the requirement for DES was identified. Other examples of sequentially mixed DES and SD projects exist in the literature, with the methods used in the reverse order and with different dominance (Chatha & Weston, 2006; Su & Jin, 2008).

Design: *Sequential* as each method is selected for specific purposes with one method distinctly being informed by and following the other in a linear process. Each method and resulting model answers specific questions. The design is summarised in Table 4.

Technical justification of mix: In this project, each method fulfilled a specific purpose; each model looked at distinct areas with only a small element of overlap as the DES was deemed suitable to provide more detail on a selected part of the system. This illustrates the importance of the system modelling view when describing a project. The sequential mixed method design involved fully developing both method models but the DES was able to utilise understanding gained in the development of the SD.

This project demonstrates how the modellers' understanding of the problem and system develop during a project and that the methodology initially selected may need to be quickly adapted. The value of mixing methods in this project is that the modellers were able to answer questions emerging during the modelling process that may not have been addressed had a single method approach been used.

4.3. Design 3: Enriching *methods*

In 1980, Wolstenholme and Coyle first demonstrated how SD can be extended to include discrete events and further applications of this design have followed.[5] This can be viewed to be an example of *Enrichment*, whereby an aspect of DES is transferred into SD modelling. SD remains the core method and is enriched by the inclusion of discrete events.

System view: Both methods take an identical view of the overall system, defining the same boundary, as the first modelling method is used to define the system and the second (enhancing) method is used within the main models.

Dominance: One modelling method is dominant throughout the intervention, with the enhancing method included throughout but embedded within the primary method.

Design: A primary method is selected to create the base model which is enriched with elements of a second method. The model is developed as a single unit and the requirement to include the second method is dictated by the problem context and the system (summarised in Table 5 and illustrated in Fig. 6).

[5] Howick and Eden (2004) also present a more recent example of including discrete discontinuities to add value to a SD project to enable the accurate portrayal of system behaviour.

Table 4
Design of combination of Brailsford et al. (2004).

Mixed method design	*Sequential* (illustrated in Fig. 5)
Level of interaction	*Zero* insights taken from each model independently, but producing the first model revealed the need for the second
Number of methods	*Two* adopting the full paradigm/modelling philosophy of each
Level of overlap	*Zero* methods remain distinct
Result of the mix	*Two* distinct standalone & independent models created

Table 5
Design of combination of enriched modelling.

Mixed method design	*Enrichment* (illustrated in Fig. 6)
Level of interaction	*Complex* One model produced that interacts with no other model. However, the enriching elements are fully embedded within and interact with the primary modelling method.
Number of methods	*Two* adopting the full paradigm/modelling philosophy of one method and enriching it with technical aspects of another method.
Level of overlap	*Full* the methods are fully mixed into a single model.
Result of the mix	*One* complete model; based on one method and containing features of another.

Table 6
Design of combination of interacting models.

Mixed method design	*Interaction* (illustrated in Fig. 7)
Level of interaction	*Complex* Two models are joined together to form a new model. Interaction between the DES model and the SD model occurs at a fixed time step.
Number of methods	*Two* both methods have been mixed to create a new method. The two models created are not used ‘standalone’.
Level of overlap	*Moderate* the methods remain distinct during development and are then fully mixed into a single model in the final phase.
Result of the mix	*One* two models are created but interact to result in a mixed single model. The two models might be used independently or in a mixed way.

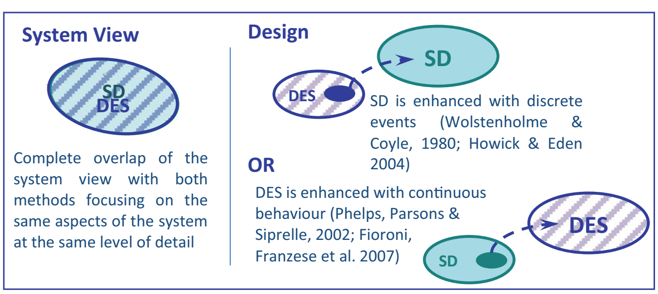

Fig. 6. Application of enhancing SD with DES or DES with SD.

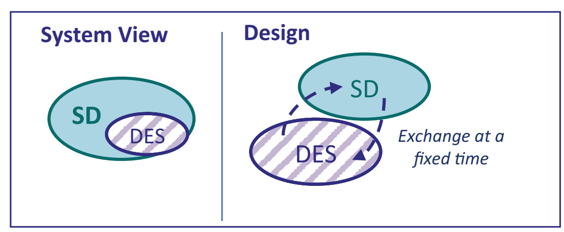

Fig. 7. Application of DES and SD model interaction.

This design has also been applied where DES has been enriched with an element of SD. Phelps, Parsons, and Siprelle (2002) and Fioroni et al. (2007) both present projects whereby a DES models continuous processes. Each of these interventions follow the original, enriched, method but have the added value of elements taken from the second method. The justification for adopting this design is driven by the needs of the model: it was deemed important to capture discrete or continuous behaviour in SD or DES respectively.

Technical justification of mix: These projects demonstrate how DES and SD were extended, with the modeller modifying the method to meet the specific needs of the project. This enrichment means that the projects benefited from the inclusion of another method without the need to undertake an additional project. However, this mixed method design requires the modeller to consider the implications of using two methods within a single model on the development, testing and validation of the model.

4.4. *Design 4: DES and SD* interaction

Venkateswaran and Son (2005) present a case where a SD model interacts with a DES model over fixed timesteps, the design of which is summarised in Table 6. In this case, the models run for a set time period and data is exchanged before the models run again for the same set time period. The DES model captures a subsystem of the SD model and new optimal values for specific variables taken from the DES model are fed into the SD model. It would appear that the two models are independent and can function on their own but there is an exchange of information between the two.

System view: Within this project the SD method was used to capture a broad view of the system and the DES represented a specific part of that system (Fig. 7) although it is conceivable that other projects may swap the roles of the methods.

Dominance: The methods are given equal dominance within the project. When the two models are run, data is exchanged at fixed regular intervals. The order in which the DES and SD models were developed is unclear but it is assumed that the SD model was initially developed which led to the requirement for the DES model.

Design: Two models are developed with the intention of creating a single final model where the two methods interact passing data back and forth.

Technical justification of mix: Three papers (Dierks, Dulac, Leveson, & Stringfellow, 2008; Donzelli & Iazeolla, 2001; Venkateswaran and Son, 2005) were identified that describe mixed DES and SD projects with an interaction design. Authors of these

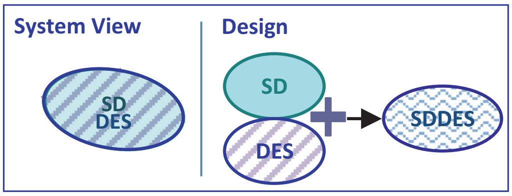

Fig. 8. Application of full DES and SD integration.

papers describe the models as valuable due to their ability to capture the operational processes and the interactive influences acting upon them. For example: allowing analysis of operational details within a "*strategic and holistic perspective*" (Dierks et al., 2008, p. 2507). This design may be described to be of use when examining two problem sets within the same system that are believed to interact and influence one another.

4.5. *Design 5: DES and SD* integration

Helal et al. (2007) present a project using full DES and SD integration which they refer to as SDDES. This particular case uses continuous time modelling with the inclusion of discrete events to simulate a manufacturing enterprise.

System view: Both methods take the same view of the system, defining the same boundary. Different aspects of the system may be captured through SD or DES methods but all are presented in the same model (Fig. 8).

Dominance: Within this project, the two methods were inseparable during the modelling process (they are assumed to be in parallel). However, how the methods interact when the single model is run is what defines this mixed method design. Events in the DES are triggered by threshold levels in the SD and vice versa; therefore there is a variable time gap between the modelled time of the DES and SD elements of the model.

Design: The two modelling methods are applied in the same model to the same problem situation, producing a single model with characteristics of both DES and SD (see Table 7). This project is a full interaction of the two methods, taking the same view of the system and integrating the methods, and with all elements of the system are represented in the same model.

Technical justification of mix: The DES features are used to represent elements of the system not captured to a sufficient level of granularity within an SD model. However, this may be difficult to conceptualise and put into practice due to the differing worldviews of DES and SD, and so it is necessary to clearly state the role each method will play within the integrated model. By adopting this mixed method design the modeller is able to work within one space and does not have to continuously move between paradigms. From a practical perspective the modeller is able to present one concise and coherent view to the 'client' of the project. From a technical perspective, it is important for the modeller to be clear as to how the two methods will interact within the single space, the timings within the model and validation.

5. A toolkit of mixed method designs

The above section provides examples of how an initial set of features, taken from the literature, can be used to identify similarities and differences between the various mixed method designs. The analysis of the example projects enabled the features to be further expanded, providing a refined set of features. A mapping between the initial set of features and the refined list is shown in Fig. 9.

Although the analysis of the examples and subsequent refinement of the features from the literature is from the single viewpoint of the primary researcher, both were reviewed by the co-authors and three further senior researchers within the mixed methods field to confirm their validity. These features aim to characterise the various mixed method designs and form part of the proposed toolkit of mixed method designs shown in Table 8. In order to facilitate use of the toolkit, the features capture the 'what', 'why' and 'how' of a project.

The toolkit is presented as a table with the mixed method designs shown in the columns and the features which characterise the designs indicated in the rows. The cells of the table were populated using the insights drawn from the review of examples from the literature. The designs are ordered according to the complexity of the mix. The designs range from maintaining the separation of paradigms, to the softening of boundaries to allow crossover. That is, the mixing of DES and SD may progress from a simple parallel design which draws comparisons or a sequential design which emphasises the order of methods and maintains separate models, to full integration where the delineation between the two methods is removed and a single model consisting of elements of DES and SD created.

The features can be used to classify, inform and reflect on projects, and the shading on the table highlights similarity across the designs to support comparison. The common language of the toolkit enables generalisability and comparability of mixed methods. It is intended as a model development aid, helping modellers to identify possible approaches and to inform modellers throughout the modelling process, rather than being prescriptive.

Methodology selection is often a personal choice and in practice the modeller may be guided by familiarity with a particular method (Corbett, Overmeer, & Van Wassenhove, 1995; Brailsford & Hilton, 2001). As noted at the start of this paper, a modeller's education and experience impact their choice of method. Work exploring the model building process of DES and SD empirically supports this commonly held view that modellers will embark on a study without first considering alternative modelling methods (Tako & Robinson, 2010). If modellers already have a methodology preference, how might we facilitate selection and find room for mixing methods in addition to use of singular OR/MS methods? We propose that a *personal filter* and an appreciation of *mixed method designs* need to sit at the heart of this selection process. Fig 10a

Table 7
Design of combination of integrated modelling.

Mixed method design	*Integration* (illustrated in Fig. 7)
Level of interaction	*Complete* The two methods are no longer distinct; they form a single model with interaction between the discrete and continuous elements at timestep (SD) and event (DES) triggers as required.
Number of methods	*Two* both methods have been mixed to create a new method.
Level of overlap	*Full* the methods are fully mixed into a single model.
Result of the mix	*One* complete model (which the authors describe as a new method).

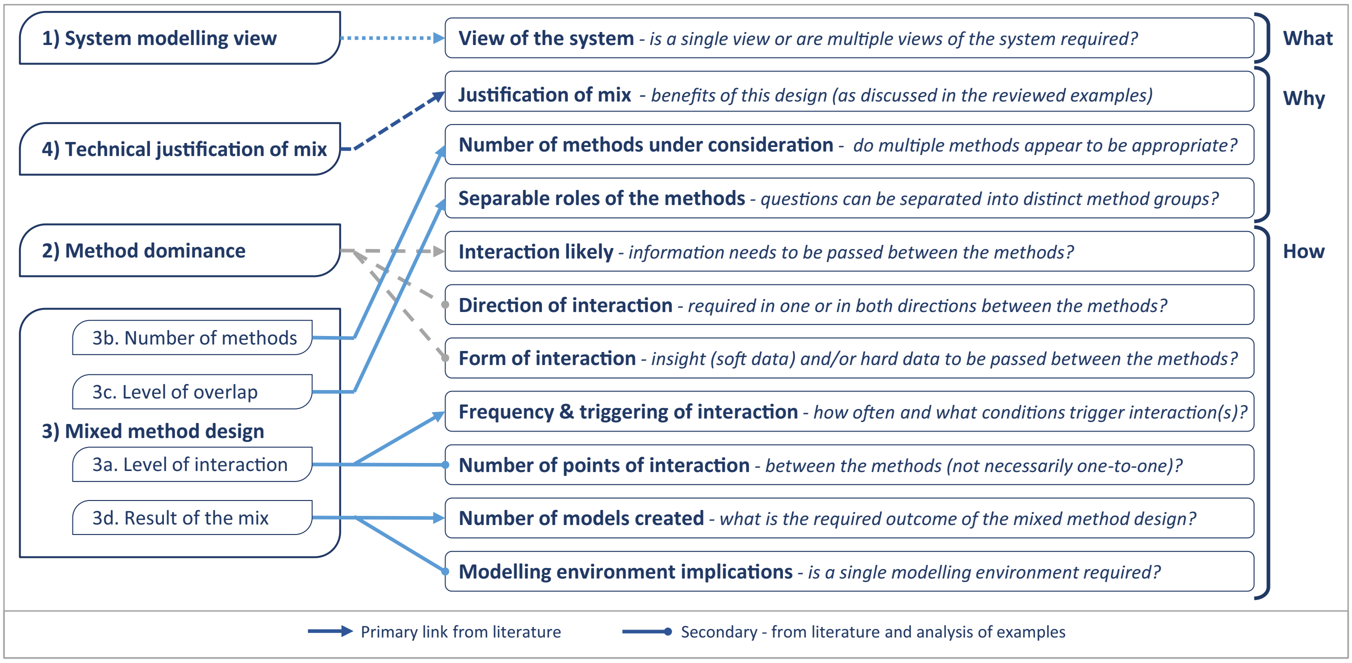

Fig. 9. Expanding features from the literature following evaluating examples.

Table 8
Toolkit of mixed method designs—a guide to mixed method designs for modellers.

	Features \ Mixed Method Design	Isolationism	Parallel Design	Sequential Design	Enrichment Design	Interaction Design	Integration Design
What	View of the system	Single view of the system	Two possible representations of the same system	Need to capture different parts/behaviours of the same system	Need to capture different parts/behaviours of the same system	Need to capture different parts/behaviours of the same system	Need to capture different parts/behaviours of the same system
Why	Justification of mix	Tried, tested and trusted methodology	Complementary insight into system to reveal plausible explanations of behaviour	Allows for emergent insights as knowledge of system improves	Benefit from characteristics of a second method without a second model	Capture interactive influences within the system whilst being grounded in each method	Capture interactive influences; present one concise and coherent view
	Number of methods under consideration	1 only	more than 1	1 or more	more than 1	more than 1	more than 1
	Number of separable roles of each method under consideration	All issues from the problem theme fit within a single method	Single problem theme requiring complementary insight	Single problem theme with issues separable into more than model	Single or multiple role(s)	Single or multiple role(s)	Single role of the methods under consideration – inseparable questions
How	Interaction likely	-	No	Yes	Yes	Yes	Yes
	Direction of interaction	-	-	One direction	One or Both directions	One or Both directions – if only one then sequential design	Both directions
	Form of interaction	-	-	Model insight and hard data	Hard data only	Model insight and hard data	Hard data only
	Frequency of interaction over time window	-	-	**Once** – single pass of information or data from one model to the next	**Low** to **high** (Likely **high**)	**Low** to **high** (Likely **low**)	**Low** to **high** (Likely **high**)
	Number of points of interaction	-	-	Single to multiple	Single to multiple	Single to multiple	Single to multiple (Likely multiple)
	Triggered or regular interactions	-	-	-	Triggered by the state of the system **AND / OR** Regular, every X timesteps		
	Number of models created	1 only	more than 1	more than 1	1 only	more than 1	1 only
	Modelling environment implications	Single modelling environment	May be built in a single or two modelling environments	May be built in a single or two modelling environments	Single modelling environment	May be built in a single or two modelling environments. Both require coding to support interaction	Single modelling environment with coding to support interaction
Comments		Modeller should remain open to adopting another method as the project progresses	Same system modelled by each method (at least two) for complementary insight	Each method captures different parts of the system or at a different level of detail.	Frequency of interaction and whether it is triggered or regular depends on the master method.	Models developed can operate independently, but work together to contribute to the problem	Methods function together as a single model.

Note: The shading on this table is used to highlight similarity across the mixed method designs.

(Lorenz & Jost, 2006) demonstrates the need to use the system and problem to define the project methodology. Adjusting this, Fig. 10b proposes to explicitly reflect that modellers have views which alter their perception of the system and problem. This filter contains bias and modellers need to seek to add an appreciation of alternative options in the form of the toolkit of mixed method designs.

The toolkit was developed by referring to the broad literature on mixing methods from both a conceptual and practical perspective and used to characterise examples of mixing DES and SD

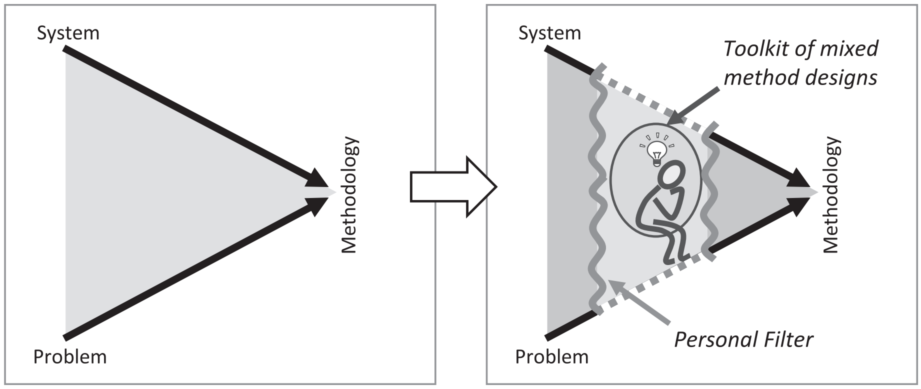

Fig. 10. (a). Methodology selection (Lorenz & Jost, 2006, p. 14). (b) Framework to inform method selection and facilitate the use of mixed methods.

from the literature. There is also significant value in its prospective use to inform future practice, which is discussed in the next section.

6. Implications for practice

This paper proposes a toolkit of mixed methods designs, consisting of questions to inform and potentially challenge key choices in the design of an intervention. Characteristics of the problem and system inform the selection of both the methods and the mixed method design. The toolkit capturing key features of mixing DES and SD is proposed for use to illustrate, describe and inform mixed method projects. The toolkit can be used in a proactive way to shed light on future projects, by offering a set of questions for modellers to consider in order to support the decision of adopting a specific mixed methods design. Modellers may refer to the toolkit to identify the design aligned with their perception of the problem and system.

The toolkit encourages the modeller to consider the input(s), the process and the output(s) of the project which all contribute to the selection of the mixed method design. It is the purpose of these designs to encourage use of mixed methods by making modellers think harder about the details of the problem and system they are seeking to model. The toolkit intends to help the modeller to consider concerns raised in the literature regarding paradigm permeability or incommensurability, lack of clarity and confusion. Therefore this work seeks to provide clarity when presenting and undertaking mixed methods work by allowing comparative evaluation of existing works and to inform further thinking and modeller choice.

The process of collating mixed method designs from the multimethodology literature provided a set of designs which cover a range of OR/MS methods (rather than limited to DES and SD). Testing the applicability of the designs on mixed DES and SD examples expanded the definitions and characteristics, leading to the proposed toolkit. Therefore, the applicability of the toolkit has been focused on DES and SD but has strong roots in the wider multimethodology field where it may be equally applicable.

When reviewing the examples in the literature, it was not possible to judge if the same results could be achieved by a different mixed method design or using a different single method. It is necessary to rely on a modeller's opinion of the appropriateness of the methods and mixed method design. However, through classifying the projects, the benefits of each design can be made explicit.

The designs presented are not intended to be an exhaustive list of possible permutations and combinations, but denote a set of designs and features identified in the literature and examples. Further designs and sub-designs may exist within each design and these may be added to the toolkit as mixed DES and SD practice develops.

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