Considering Combining: Designs for the complementary use of System Dynamics and Discrete Event Simulation

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Abstract: *System Dynamics (SD) and Discrete-event simulation (DES) can be viewed as complementary approaches to modeling. Both are popular simulation approaches and have been applied in a wide range of situations for various purposes. Reviewing the literature from the multimethodology field allows us to develop a modeling framework that considers the differing ways in which SD and DES could be combined. The aim of the work described here is to test, reflect on and further develop this framework through an intervention, and to examine how the modeling approaches can be combined in practice.*

The paper discusses models under development with a radiotherapy center to explore the impact of altering treatment regimes for patients in response to the adoption of new, more complex, technology. The questions posed within this project lend themselves to exploration using both SD and DES and the work explores the potential to combine their use in a way which is both complementary and synergistic. The SD model developed in conjunction with the radiotherapy center is discussed along with the proposed development of a DES to provide further insight. The paper concludes with reflections on the experience to date and learning with regard to the proposed methodology.

Keywords: *Health, Mixed modeling, Discrete Event Simulation, System Dynamics*

Introduction

System Dynamics (SD) and Discrete-event simulation (DES) are popular and widely used modeling approaches and their potential to provide benefit when applied to healthcare situations has been clearly demonstrated (Taylor & Lane 1998; Cooper et al. 2007). In addition, the potential for complementary use of the approaches has been discussed within the broad simulation community (Renshaw 1991; Morecroft & Robinson 2006). However, how to create complementary insights, and how the approaches may be combined, both in theory and in practice remains up for discussion.

Examining the multimethodology literature reveals numerous designs for mixed modeling in theory (specifically: Bennett 1985; Schultz & Hatch 1996; Mingers & Brocklesby 1997) and allows consideration of their applicability in practice to the combination of SD and DES. This research adds to this literature by providing a framework and a single set of designs that can be used to inform the development of mixed modeling projects and by examining the application of these designs through a practical project.

The following section will discuss the background to this research, including a brief comparison of SD and DES, motivation within the community to utilize combining and the areas where further work is needed. Following this, a framework for methodology selection is proposed and a set of designs for mixing modeling approaches is developed from multimethodology literature. Finally, these designs are applied to a case study to explore their potential applicability and relevance.

Background

SD and DES have been successfully applied to a range of health situations (Brailsford & Hilton 2000) and are both prevalent yet distinct approaches in the systems modeling field. Previous work has highlighted the potential to offer complementary insights with benefits found in combining them as using both prevents becoming "*trapped by deterministic fantasy or unnecessary mathematical detail*" (Renshaw 1991, p.2)

SD is used to discover underlying principles and behavior of complex systems over time (Forrester 1958), capturing the average flow of the system. The efficacy of SD is born from its ability to capture the whole system rather than focusing on short term goals and single measures of performance, which can lead to ineffective conclusions (Taylor & Dangerfield 2005). It offers a methodology to assist strategy development and policy analysis, capturing information flow and feedback (Sweetser 1999) which is useful within Healthcare to evaluate the long term impact of complex policies (Kuljis 2007). SD models are, in general, a macroscopic view of a system, with an interest in how the system structure impacts the system behavior, recognizing that the behavior of individual components of a system is distinct from the behavior of the system as a whole. There are many proposed processes for undertaking SD interventions, but each contains similar stages[1] cyclical in nature, with a clear view to reflect on and revisit the stages of the process referencing the real world throughout (Randers 1980).

DES is a simulation approach where the dynamics of the system are driven by events, allowing users to model the individual events experienced within a system, modeling at the entity level to explore progression through a system (Pidd 2004). It can be applied to explore a system's ability to meet targets and cope with changes, and is often used to represent systems at an operational level, where the individual detailed interactions and experience of entities over time is important and the variation in service experienced may be a key measure. The model development process of DES is also cyclical but less so than SD (Tako & Robinson 2008). Overall, DES has a characteristic style but may be applied in a variety of ways and have different characteristics depending on the problem situation it is applied to, as demonstrated in Figure 1. Its application may be described as hard when seeking an accurate representation of a situation (simulation as software engineering) and soft when utilized for problem understanding (Robinson 2002).

[1] Model development stages: conceptualization; formulation, testing and implementation

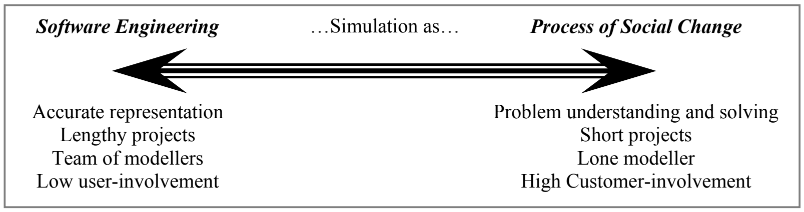

Figure 1: Modes of Simulation Practice adapted from Robinson (2002) highlighting the range of DES application in practice

This discussion of SD and DES illustrates that it is not possible to simply map and compare the approaches to reveal potential for combination. It is necessary to obtain an understanding of the situation under study and then explore the potential modeling approaches and whether it is beneficial and appropriate to combine them.

Randers (1980) presents an early comparison of SD with other forms of quantitative modeling[2]. Comparisons of SD specifically with DES are also made by Sweetser (1999), Lane (2000), Brailsford & Hilton (2000), Morecroft & Robinson (2006), Tako & Robinson (2008) and Chahal & Eldabi (2008). However, many of these pieces of work seek to place the two approaches into distinct boxes rather than appreciate the range of characteristics and their similarities. Both approaches are described as providing value and insight to the systems they seek to capture and the problems they aim to address. Sweetser comments that: "*Many problems could be modelled by either approach and produce results that would look very similar*" (1999, p.8). Both tools are suitable for providing increased understanding and aid decision-making and, in reality, the two approaches demonstrate significant overlap, illustrated in Figure 2.

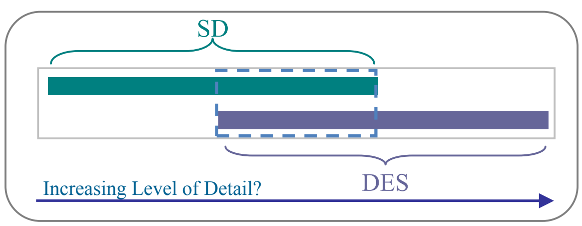

Figure 2: The possible continuum of SD and DES

All useful simulation models (SD and DES) are simplifications of reality but each approach simplifies differing aspects of a system (Meadows 1980; Pidd 2003). A meta-comparison by Chahal & Eldabi (2008) comparing the approaches from three perspectives is summarized in Table 1. The perspectives - Problem, System and Methodology - need to be aligned to develop sound models (Pidd 2004). Similarly, if the methodology employed within an intervention comprises of more than one approach a fit with the system and problem is also required. The following discussion of SD and DES is based around these perspectives.

[2] Randers (1980) discusses models for prediction versus models for understanding, which Lane (2000) concludes to refer to DES versus SD.

Table 1: Summary of Meta-Comparison of DES & SD developed from Chahal & Eldabi (2008) and Lane (2000)

	DES	SD
Problem	Seeking to understand the impact of randomness on the system	Aiming to understand the feedback within the system and its impact
	Operational	Strategic / Policy
System	High level of detail that physically represents the system (detail complexity)	More macro level of detail that summarises the system (dynamic complexity)
Methodology & Philosophy	Process view	Systems view
	Randomness	Feedback

Embedded within each approach are its philosophical assumptions and principles. A primary concern when considering mixing approaches is the issue of paradigm compatibility as both SD and DES have quite separate modeling philosophies (Lane 2000). SD is focused on how causal structure results in observed behavior, whereas DES focuses on performance over time, illustrating how randomness influences the systems behavior (Tako & Robinson 2008). However, these differing philosophical views, coupled with capturing a system and its problems at different levels of detail, may yield interesting alternative insights.

Both approaches are described to be of use in developing understanding of a system (Tako & Robinson 2008). SD is used to appreciate how a system alters over time; the impact structure has on the system (Owen 2008). DES is used to understand a systems behavior and explore different configurations. There is no question that each approach has its place, but the primary difference is that DES does not obviously allow the user to understand the underlying mechanics of changing information and feedback; whereas these links and flows are transparent in SD (Tako & Robinson 2008). Borshchev & Filippov (2004) discuss that a cross over from DES to SD would be due to the nature of the problem at hand: a diverse and complex system, with hundreds of thousands of entities, and queues less important than the process flows.

The choice between DES and SD "*often seems to be made based on an unknown, or at least unstated, user preference function*" (Koelling 2005, p.1322). If SD is efficient in policy design interventions and DES is efficient with policy implementation problems (Ceglowski et al. 2007), the question arises: can we have both? As simulation modeling can be time consuming (An & Jeng 2005), could a mixed approach help to reduce the time taken to produce useful, insightful models or increase the applicability and overall use of models?

This discussion leads to the question of when it may be appropriate to combine the approaches, and how they may be used together in a complementary fashion. SD and DES have been combined with, or supported by, other modeling approaches such as statistical analysis, data mining, problem structuring, optimization, Multi Criteria Decision Analysis and process flow mapping. Few papers bringing DES and SD together exist in the literature, some examples are:

- Using SD and DES to model the same system and provide comparative insights into fisheries (Morecroft & Robinson 2006).
- An initial application of SD within a health project in which the need for DES became apparent (Brailsford et al 2004).

- Applying DES then SD to inform healthcare facility design and predict implementation problems respectively (Su & Jin 2008).
- Full SD and DES integration referred to as SDDES to utilize continuous modeling whilst including discrete events to simulate a manufacturing enterprise (Helal et al. 2007).

Following the above brief comparison of SD and DES the next section will consider how the two may be formally combined to provide a holistic view of the system, encapsulating the benefits of each method. It will present designs that may be appropriate for bringing the approaches together.

Modeling Frameworks

When embarking upon a simulation study two aspects should be examined to decide the level of accuracy and detail required in the model: the nature of the system (system) and the nature of the study (problem) (Pidd 2004); merely examining the problem perspective can be misleading (Lane et al. 2000). Further to this it is important to avoid using the modeling methodology as a starting point for a project, and "*select the most suitable methodology for a given purpose and object*" (Lorenz & Jost 2006, p.14)[3].

When learning a modeling approach, a modeler is encouraged to view a system in a certain way and this impacts their choice of tool. Methodology selection is often a personal choice and in practice the modeler can be guided by familiarity with a particular approach (Brailsford & Hilton 2000). Proponents of a specific approach should take a "*step back and assess which conceptual toolkit should be used*" (Chick 2006, p.22). Work exploring the model building process of SD and DES empirically supports this common held view that modelers will embark on a study without first considering alternative modeling approaches (Tako & Robinson 2008).

If modelers already have methodology preference, how might we facilitate the selection process to find room for further options to combine approaches? An individual modeler's experience and preference plays a significant role in the selection process, this would suggest that a personal filter and appreciation of linking designs needs to sit at the heart of this selection process and Figure 3 is proposed. This framework represents the need to use the system and problem to define the intervention methodology, but explicitly represents the personal filter of modelers that alters their view of the system and problem. It is proposed that this filter contains bias and modelers should seek to add an appreciation of alternative options.

[3] Lorenz & Jost use the terms purpose and object which aligns with problem and system (as defined by Pidd 2004).

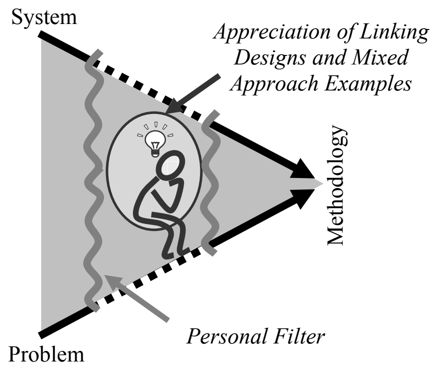

Figure 3: Selection of appropriate modeling approaches

Combining modeling approaches raises many philosophical issues[4]. For some it is not conceivable to separate an individual approach from its theoretical backdrop and so when considering mixing approaches it is necessary for the modeler to think at a paradigm level. A major concern for multimethodology is the concept of paradigm incommensurability: the view that paradigms are independent and incompatible as they are based on differing assumptions (Mingers & Brocklesby 1997). Cultural and cognitive concerns impact the feasibility of multimethodology studies as organizations and individuals may not be open to the idea of the approach (or from moving from one paradigm to another). However, real-world problem situations are highly complex and multidimensional; and potentially may benefit from different paradigms[5] to focus on different aspects of a situation. In the same way that Lane (2000) proposes appreciating both SD and DES to develop a richer understanding; this research proposes that an awareness of mixing would allow us to capitalize on the opportunities it holds.

Examining the multimethodology literature reveals several designs for undertaking multimethodology in theory and their applicability in practice which can in turn inform the combination of SD and DES. Three key works, which explicitly discuss a range of forms for combining modeling approaches, are:

Bennett (1985) represents an early discussion of linking methods in which three forms are considered:

- *Comparison* as a precursor to more ambitious forms of combination, revealing where they are compatible or complementary.
- *Enrichment* involves using one approach to enrich another resulting in a single model and allowing for the transfer of ideas.
- *Integration* consists of using elements of existing approaches to provide something new.

Schultz & Hatch (1996) highlight the importance of the order of combination when combining approaches, by summarizing the possibilities as follows:

- *Sequential* application of approaches, whereby the two remain operating within separate paradigms, one after the other.

[4] Mingers & Brocklesby (1997), Mingers et al. (1997) and Lane (2000) discuss this at length.
[5] or indeed tools, techniques, methods, or methodologies

- *Parallel* refers to different paradigms applied on equal terms (at the same time) rather than sequentially (similar to *Comparison*).
- *Interaction* describes where paradigm boundaries are viewed as permeable allowing connections and contrasts between the paradigms (may take several forms).

Mingers & Brocklesby (1997) discuss the overall spectrum of methodology selection, from a single approach to fully combining two approaches:

- *Isolationism* refers to adopting a single methodology, or techniques from a single paradigm.
- *Enhancement* involves enhancing one methodology with techniques from another. The methodologies may or may not be from different paradigms.
- *Selection* describes picking whole methodologies for different interventions.
- *Combination* of whole methodologies within an intervention.
- *Multimethodology* partitions methodologies and combines parts which may operate within the same or different paradigms.

Examining these *linking designs* reveals points of commonality and a refined set of terms are proposed to eliminate overlap. These collated terms are proposed for use when considering undertaking (to inform design), describing (for reporting) and reflecting on existing multimethodology:

- *Isolationism*: Adopting a single approach (including *Selection*)
- *Parallel*: Incorporating *Comparison*, where approaches are applied independently and comparisons drawn at fixed points.
- *Sequential*: One approach follows another.
- *Enrichment*: A primary approach is enriched or enhanced with approaches from one or multiple paradigms (including *Enhancement*).
- *Interaction*: Paradigm boundaries and restrictions are relaxed allowing connections to be made between approaches.
- *Integration*: Complete, or elements of, approaches are combined to form a new approach. As *Multimethodology* is often used to refer to the mixed methods field it is proposed that *Integration* is adopted as the term of choice.

This research continues by examining the use of a 'toolkit' of designs in practice through a healthcare project and takes the following form:

1. ***Problem & System Exploration:*** The principles of the framework, to examine the system and the problem, are adopted during the project to inform methodology selection and design. A problem structuring approach successfully applied to both SD and DES is employed to reduce bias.
2. ***Select Issue & Examine Characteristics:*** The focus of the project is selected and comparisons of SD and DES are used to identify options for modeling the issues. It is here that consideration is given to whether a single methodological approach would be preferable and what benefit a mixed approach might provide.
3. ***Designing Combining:*** This will be complemented with the toolkit of designs used to support the structuring of the problem and framing of the project. The designs will be utilized to reflect upon how the project issues may be addressed by a complementary use of SD and DES and how this combination can occur in practice. Considering the *Linking Designs*: are there distinct elements of the

issue(s) applicable to different modeling approaches (*Isolationism*), might one modeling approach be enriched in order to capture the issue adequately (*Enrichment*), would the issue benefit from being explored with one modeling approach first (*Sequential*)?

4. ***Model Development:*** Initial stages of model development are discussed.

The following section discusses a project that is currently in progress which applies the ideas discussed above. The focus of the project is on the Radiotherapy processes within an oncology center. The initial problem structuring stages of the process are discussed illustrating the unique roles that SD and DES may take along with their potential complementarity. Preliminary models are presented and the proposed methodology is reflected upon.

Project Application – The Beatson Oncology Centre

The Beatson West of Scotland Cancer Centre is Scotland's largest cancer center serving a population of 2.6 million. The center provides holistic cancer care, but this project is focused specifically on Radiotherapy, with the center delivering over 300 doses of radiotherapy per day (www.beatson.scot.nhs.uk/).

Radiotherapy can be used to eradicate cancer cells to eliminate disease (radical treatment) or to relieve cancer symptoms (palliative treatment). Patient Treatment is a complex, multistage process that intends to cause as little harm as possible to normal cells by aiming the treatment at the affected area of the body and requires careful planning and to be tailored to individual patient physiology. The key stages involved with radiotherapy are booking, simulation, planning and treatment. These are interrelated stages with feedback throughout as a patients plan may need to be altered, scans may need to be redone or numerous treatment plans may be produced as illustrated in Figure 4.

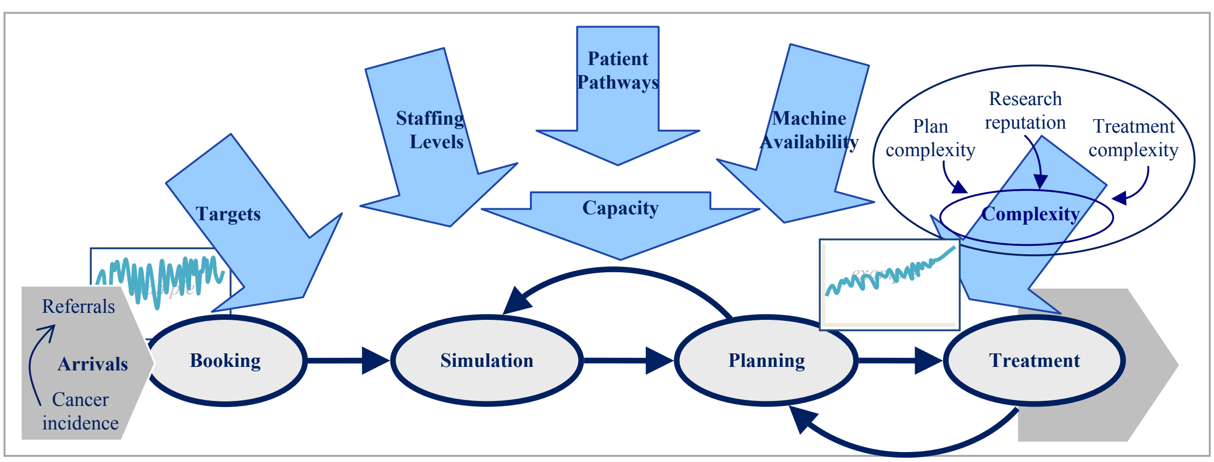

Figure 4: The Beatson Radiotherapy Process

Previous successful projects within the department have separately examined strategic and operational issues with SD and DES respectively. The department continues to face numerous strategic and operational issues, with external and internal influences, and this project provided the client with an opportunity to choose to examine these with a new lens, bringing a new perspective.

The problem was not well defined and it was necessary to examine potential areas for investigation and determine focus. Causal mapping was used for this purpose as it has been successfully applied, with both SD and DES, as the means of initially surfacing, capturing and structuring issues. Areas for exploration were identified and possible suitable modeling approaches considered. A problem area for initial focus was selected based on the questions being asked being both SD and DES-like and the initial phases of work are discussed.

1. Problem & System Exploration

The initial phase of the project was to explore the system and structure the problem by eliciting issues and views from stakeholders using techniques equally applicable to each SD and DES[6] to enable issues to be explored in an unbiased manner. Causal mapping was selected as a suitable approach to apply when looking to explore muddled, complicated, dynamic world where everything is interconnected as it provides a means to formalize the structure (Montibeller & Belton 2006). This mapping phase is utilized to focus on the beliefs, values and assumptions an individual has about the system and reveal issues. Causal mapping enables large amounts of information to be collated, permitting the exploration of both detailed and holistic properties (Ackermann & Eden 2005). It provides a structured process to record stakeholder views and adds richness by recording interrelationships between concepts.

Individual interviews were conducted with 7 stakeholders selected to represent a range of views held within the Radiotherapy department, including management, clinicians and radiotherapy staff. These interviews were semi-structured and aimed to explore the system of interest, highlight aspirations, expose areas of concern, and eventually lead to definition of the problem area(s). Interviews were mapped and examined to identify key themes which were then used to collapse the maps to gain a summarized overview of the interview[7]. These individual maps were then combined to be developed into a causal map of the system. Clusters from the individual maps were re-examined to locate concepts with corresponding meaning, and repositioned on the merged map to provide an overall clustered map.

When embarking on the problem definition stage of a project the modeler may hear what they want rather than what a client means (Vennix 1996). It is for this reason that it was deemed important to return to the interviewees and gain confirmation that the resulting group map of the system, reflects interviewees' views. The problem structuring process undertaken is illustrated in Figure 5.

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[6] Causal mapping has been used successfully as a precursor to SD and DES modeling

[7] Based on how clearly they were described by the interviewee, their centrality to the rest of the map and the emphasis put on the topic (if the interviewee returned to or mentioned the topic numerous times it was highlighted).

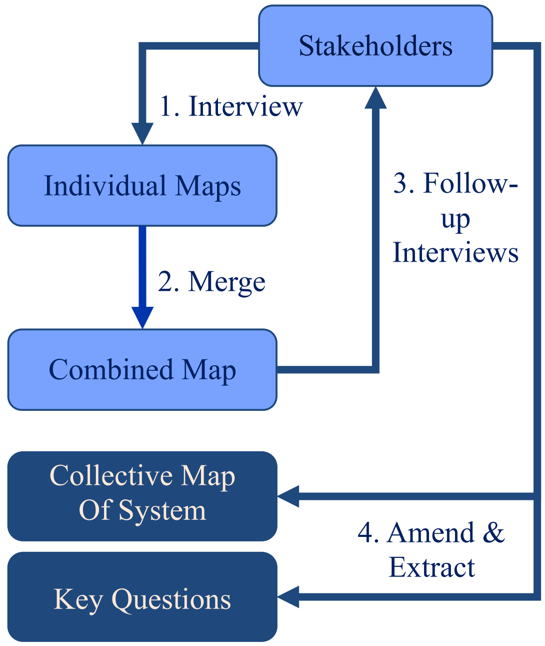

Figure 5: Interview and mapping structure

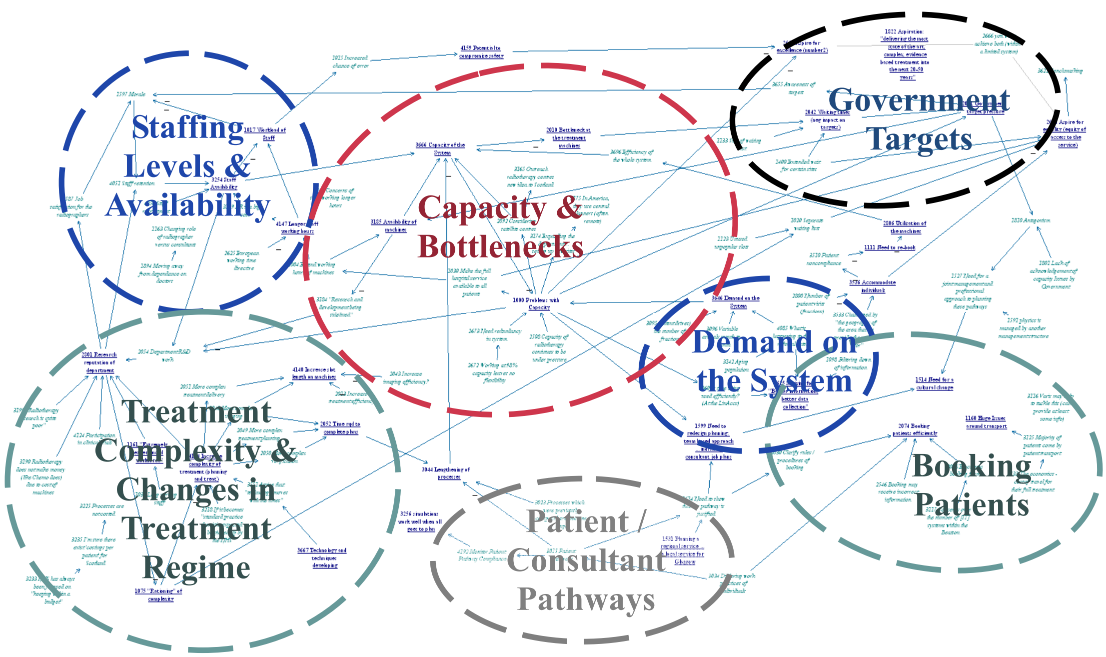

Figure 6: Collective Causal Map of System after follow-up interviews[8]

[8] It should be noted that for the purpose of the paper it is not the intention that the individual concepts within the cause map be readable, instead the purpose of figure 6 is to highlight the key themes that emerged

2. Select Issue & Examine Characteristics

Several key themes and many questions were surfaced and Figure 6 shows the collective map with these areas of concern highlighted. This diagram illustrates the interconnectivity and overlap of the key concepts identified within the map. The issue selected for the first study was *Treatment Complexity and Changes in Treatment Regime*. This problem area was selected due to the immediate nature of the questions being posed (the department is regularly considering implementation of new regimes) and the knock-on impact this aspect has on the capacity of the system and the strain it is put under by increasing workload and requiring new techniques to be learnt.

Changing Treatment Regimes

Radiotherapy treatment regimes consist of a plan devised for the treatment of a patient and a series of treatment fractions[9] administered on a linear accelerator. Treatment dosage and the number of fractions are planned by physics staff; and the complexity of these plans can vary for the different cancer types and the characteristics of the patient's disease.

Radiotherapy Research and development, advancements in technology, and changing best practices mean that new techniques become available to physicists for the treatment of cancer. The Beatson has to decide which treatments to make available to patients and how these can be rolled out across the system. Different developments can have differing impacts on the capacity of the system as some may increase efficiency within one part of the system but limit capacity at others (free up treatment machines but increase the time required for physicists to plan treatment). The Beatson must assess whether to implement changes in regime at regular intervals (potentially every few months).

The nature of the problem is summarized in Figure 7. This diagram is developed from the collective map, following the second round of interviews to clarify the issues in focus. The map reflects the aspirations of staff (seeking to maintain its reputation for clinical excellence), whilst ensuring that the impact of implementing new regimes does not negatively impact KPIs and equality of access for patients. It also reflects the impact changing radiotherapy techniques has on the capacity of the system by changing the time required to be spent scanning/imaging patients prior to planning, the increase in the time required to plan patients, the increased need to verify plans when new regimes are implemented, and the additional time that may be required on treatment machines.

[9] Treatment fractions are the number of daily visits to the radiotherapy center to receive treatment

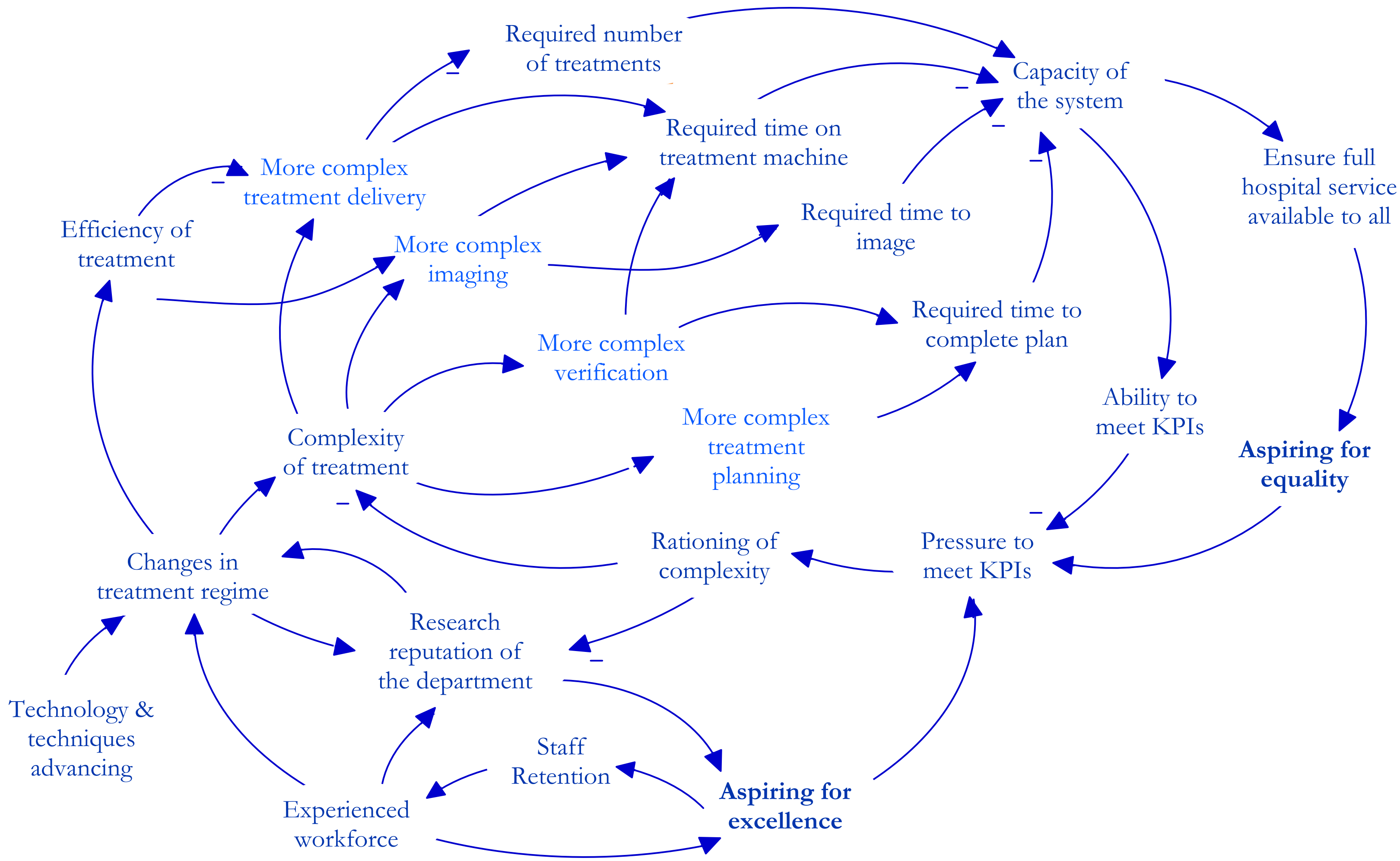

Figure 7: The Problem – Increasing Complexity and Changing Treatment Regimes

The maps and interviews were re-examined to determine the key questions being posed around this theme and generate Figure 7 to provide an overview of the causality:

1. *What is currently provided at the Beatson and how is availability impacting equality?* How many patients are currently treated per month, how quickly are patients reaching treatment and how variable is this across patient groups?
2. *What is the knock-on impact of changing treatment regimes?* If new treatment regimes are implemented, will it be possible to maintain current throughput; what if we change the mix of regimes; and when will the system fail to cope?
3. *What is the impact on different patient groups?* Will some patients receive a longer wait, will new regimes only become available to cohorts, and will this lead to bottlenecking in the system?
4. *What can realistically be implemented and what resources would be required?*
5. *What would be the impact of a policy change regarding regimes?*

On examination of these questions some appear more amenable to exploration using SD modeling and others to DES[10]. These questions display both SD and DES characteristics and a mixed approach would allow exploration of both goals, but a single approach would require several assumptions about behavior to be made. In an SD model, it would be necessary to assume all patients behave similarly and is not designed to reveal the range in variability patients may experience within the system. Conversely, within a DES it would be necessary to assume a fixed plan for the implementation of more complex regimes and not allow exploration of the systems propensity to cope with pressure (feedback within the system to reduce complexity).

3. *Designing Combining*

After re-examining the collective map and summarizing the questions above, two key goals become apparent:

A. Explore the dynamics of government targets interacting with R&D adoption
B. Examine the day to day impact of changing the treatment regime

The proposed design for this project is to use SD to capture the dynamic nature of the problem (Goal A), whilst using DES to appreciate the impact on the day to day running of the center (Goal B). It is felt that the two approaches have explicit roles to play within the modeling intervention and that a complementary approach to modeling be adopted.

In order to examine the day to day impact of changing treatment regimes it is necessary to develop an understanding of the general influence complex technology adoption can have on the system. As discussed in the previous section (modeling frameworks), consideration is given to how the two approaches can be combined in practice and it was deemed appropriate to adopt a S*equential* project design (SD then DES) with the possibility of *Interaction* once sufficient appreciation of the system was developed and points of exchange identified.

[10] Based on the level of detail within the question and referring to comparisons of SD and DES to inform selection: Q1 - DES, Q2 - SD & DES, Q3 - DES, Q4 - SD & DES, Q5 - SD & DES

SD was selected to be used first, to explore the wider system and how government targets and the pressure to maintain low waiting times alter the behavior of the system. It is proposed that this model will then be complemented with a DES that is able to examine the individuality of patients' treatment, and the impact altering regimes has on access to the system.

Alternative linking designs, as discussed in the Modeling Frameworks Section, have also been considered:
Parallel – Developing the models in parallel may result in increased workload as both models take overlapping views of the system. The focus of the SD model is on the wider system behavior and the DES intends to explore the physical processes within the Beatson. Development of the DES appears to require significant insight into the system that it is possible to develop whilst constructing the SD model.
Enrichment – was considered a viable option as stochastic elements of the system could be represented with the SD model. However, this approach would not provide a sufficient level of detail to the client, and would require a lot of changes, subscripts and randomness to be included in the model.

Initial Phase SD Model

An initial SD model was developed to capture the dynamics of the department responding to increasing waiting times by reducing the complexity of the treatments adopted. The CLD in Figure 8 illustrates that as treatment time increases, days to treat increase resulting in increased waiting times. In response to increased waiting times, the system tries to reduce treatment times (and hence limit complexity). This model was used to illustrate the potential management of the system to ensure that the waiting times experienced by patients do not exceed government targets (or some other desirable level) by adjusting the patient treatment time to suitable appropriate levels. Delay is built into the model to reflect the time it takes for waiting times to be reported to management and thus to allow for a change in behavior. This model captures the pressure to drive down waiting times, illustrates the careful balance that needs to be maintained within the system and that treatment time needs to be managed carefully. The Beatson treatment process is modeled as a single stock and flow, but may be broken down further using a DES to include the intricacies of the flow of patients.

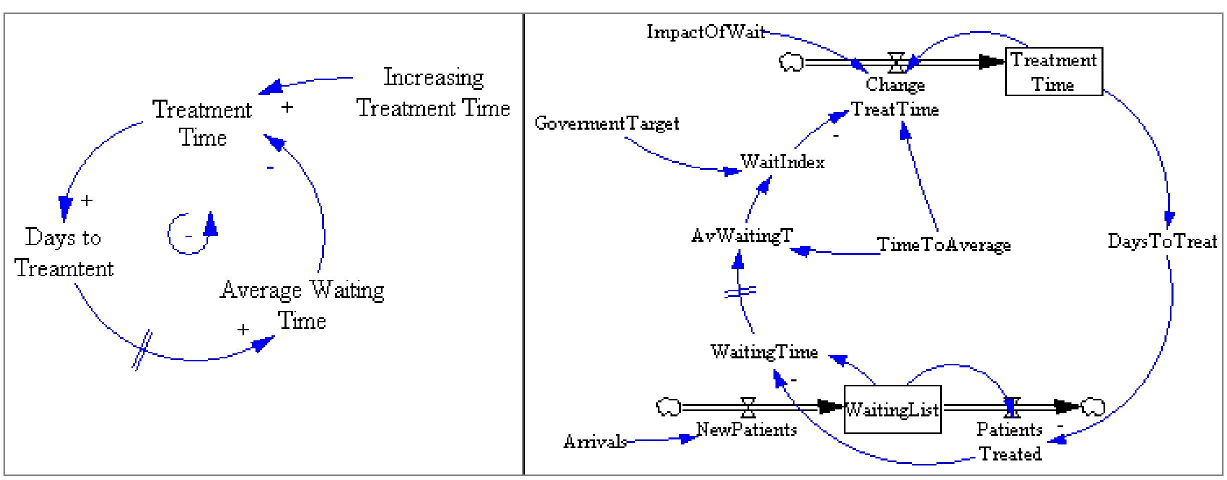

Figure 8: Initial Treatment Regime Model - Basic Causal Loop Diagram (CLD) and Stock and Flow

Second Phase SD Model

The initial SD model represented a simplification of the real case as it assumes that treatment times can be directly altered. In reality it is the decision to reduce the number of complex procedures that results in a reduction in the average treatment time and this is included in the second phase of the model. Also when new, more complex treatment regimes are adopted then the initial impact on treatment time is higher than the 'expected' average level due to the learning process involved.

A more important aspect included within the second phase SD model is that staff (in the first instance) will try to manage the queue by working longer hours, and the center could seek to maintain complexity by allowing working hours to alter in response to the waits experienced. The overall causal structure of this model is depicted in Figure 9 (this model is still being developed and further explanation of the relationships within the model is provided in the Appendix).

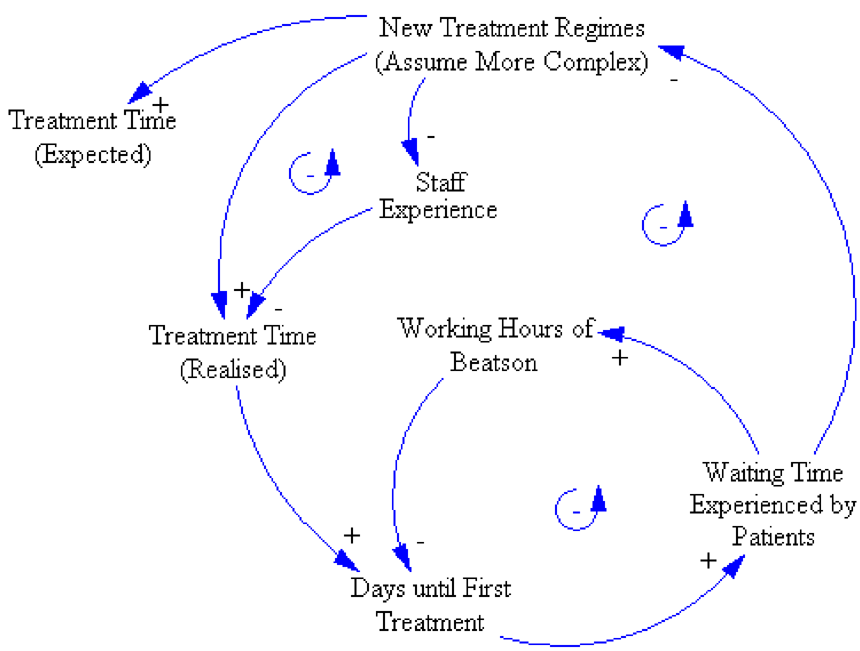

Figure 9: Overview of SD Model of Treatment Regimes Impacting Patient Waiting Times

Following this SD model development, the need for a more detailed representation of the core Beatson process, as shown in Figure 4, has become apparent. Within the SD model this part of the system is modeled as a single stock and flow and the potential to add value lies in including a more realistic depiction of the physical treatment of patients. The SD model currently represents the populace behavior of the system but further value can be added by considering the individualistic behavior of patients and their respective treatment plans. Although further detail can be added to the SD model, a DES model is a more apparent choice given the operational nature of the questions posed, the desire to represent the stochastic behavior of individual patients, resources and processes and level of detail to be attributed to the model.

Initial Phase DES Model

The Beatson process has numerous resource restrictions, varying treatment regimes, and a range of routes a patient may take to receive treatment. This means that an increase in treatment complexity can have variable impact on the wait time experienced by different patient groups. A DES model is in development to provide more representative insights into the knock-on impact of altering the treatment time or number of treatment fractions for different groups of patients. The intention of this model is to assess the impact of treatment regime changes on the variation in time for patients to reach treatment, ensuring equality of care for all patients in a timely fashion.

The first phase of the DES model development is shown in Figure 10. This model captures the four key stages of the Beatson process, the cycles that often occur between these stages and the resources required at each stage. Within this model, patients arrive and are routed through the system depending on their cancer type and how their consultant intends them to be treated. Each patient is tended to by their assigned consultant throughout the process and their treatment plan is produced by a qualified member of the planning staff. In the simplest case, a patient continues to treatment, linearly moving through the process. However, in many cases, especially in more complex treatments, the patient may require multiple treatment plans or their plan to be altered, often requiring scans to be redone. This adds further load to the system at all stages of the process (as changes to imaging or treatment times incurs additional work at the booking office).

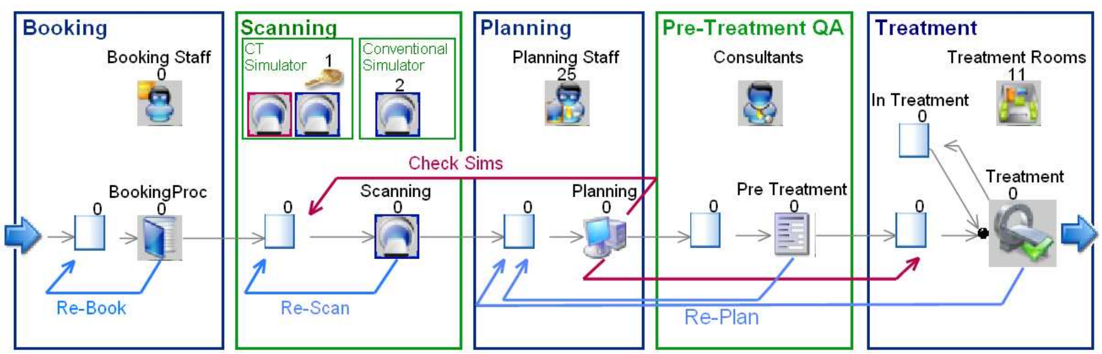

Figure 10: Screenshot of Initial DES model capturing the four core stages of the Beatson process

It is easy to assign individual characteristics to patients within a DES model, and this has been incorporated into the initial model, providing a richer representation of the waiting times experienced and the resulting variation across patients than could be gathered from the SD model in its current form. This model will be extended to include staff and machine timetables along with a breakdown of the planning and checking processes to capture the planning pathways observed in the real system. This second phase of the model will allow assessment of the impact of shifting the flow of patients through these pathways to represent the changes in treatment regime. It will enable the unit to carefully consider the adoption of such changes in regime and how they can implement these changes whilst minimizing the impact on the average waiting time, the overall throughput of the system and the potential variation in wait times experienced by patients, which may in turn reflect upon the equality of treatment. The design of this study is *sequential*, using SD to explore the wider context of the problem and develop initial understanding of the concepts involved, followed by DES to consider how to implement changes at ground level.

Discussion

The complementary use of a DES will allow examination of the variation in the impact felt by increasing treatment times or changing the treatment (and planning) mix. This developed understanding of the knock-on impact can then be used to inform the SD model and the relationship between treatment time and the resulting time a patient takes to progress through treatment (the wait). By examining the problem through the proposed framework with the view of combining modeling approaches it allows the system to be analyzed at several levels of detail and enables the wider policy issues to be explored. In the past, the key contact for the project has been drawn to data intensive detailed analysis of the system which is not always practical due to data limitations. This approach has enabled wider issues to be examined and the general impact of policies on the overall functionality of the system to be assessed before examining the impact at a patient level. It has enabled new questions to be posed and reflections to be made on how the center functions. In addition, the approach has highlighted what measures might be used to assess performance through discussion around the use of throughput versus waiting times versus treatment outcomes[11].

For the Beatson project a SD model has been created and could be made more complex to include much of the DES's functionality. However it is believed within this project that this would stretch and contort the SD paradigm. DES is proposed for use to add value to the modeling of the treatment process, and then the two models may be linked. The design of this intervention is *sequential* (SD then DES) with the view to have the two models *interacting* to provide further insight. This case illustrates that the problem dictates the linking design adopted in practice. In theory there is a wide range of linking options available to a modeler, but in practice it is necessary to carefully consider the practicalities of the design adopted ensuring that it is the most efficient use of the modeler and the client(s) time and resources. Within the case it is possible to develop large complex models and apply the range of linking designs available, but these may not fit with the clients' desired outputs, including unnecessary detail.

SD and DES may be viewed from several perspectives and applied in a variety of ways depending on the modeler and thus it is necessary to evaluate the suitability of mixing approaches on a case by case basis. The purpose of this work is to explore how the approaches may be used together to provide complementary insight into a situation, and how the two approaches may interact to provide such insight. The linking designs are intended to aid the planning of an effective intervention: to inform the development of the models and their combined use, enable clear discussion of the form the combination may take, and provide a coherent set of designs for implementation. Although this work focuses on the potential benefit of mixing SD and DES, the designs may be used to explore the mixing of other modeling approaches. The work therefore contributes to the wider field that reflects the practice and theory of multimethodology.

[11] No data is captured in order to assess treatment outcomes.

Further Work

This paper presents a work in progress, with the DES model currently in development. Once the models are in a position to adequately reflect the system, capturing the key features of behavior of interest, it will be possible to further assess their overall usefulness and applicability within the context of the case, their suitability for answering the questions posed and reflect on the insights gained. Feedback from the stakeholders has been positive throughout the project, but once the models are adequately developed it will be possible to engage with the stakeholders and assess their personal views on the process undertaken. This would allow reflection on the modeling methods adopted, how the two methods are perceived, and their usefulness within this case. This would also provide an opportunity to gain insight into how practical and relevant mixed modeling is viewed to be, and the potential usefulness of the overall process undertaken.

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Appendix

Complexity & Learning

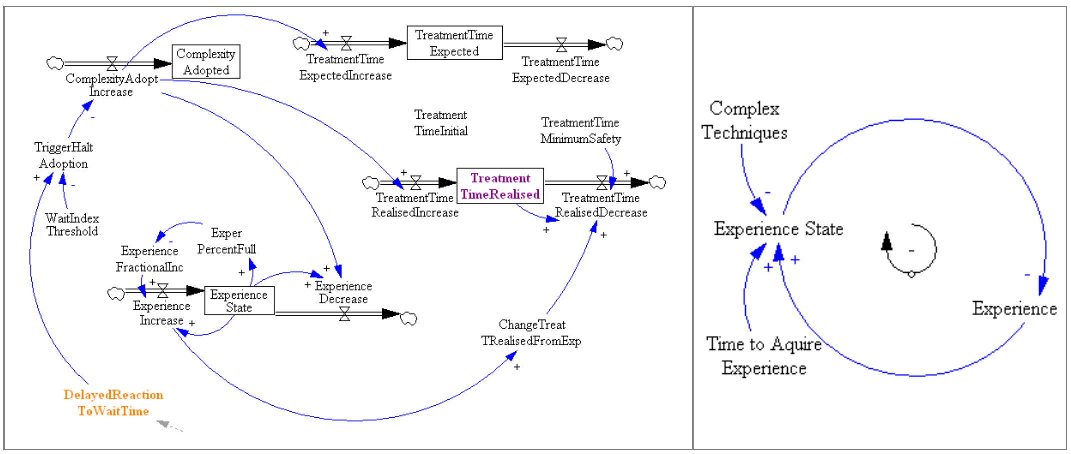
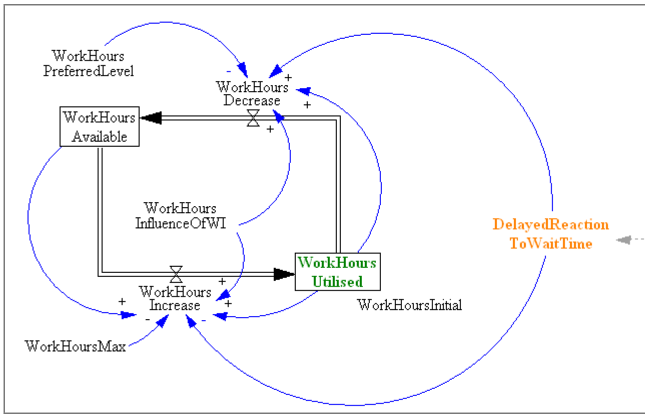


Figure 11: Increasing Treatment Complexity leading to increased Treatment Times and reduced Experience State and Causal Loop Diagram of Experience

Figure 11 includes a learning process to describe the reaction within the Beatson to the arrival of a new more complex technique. The knowledge and experience related to this technique is zero at the start and builds over the course of some time period (for example 30 days). This learning follows an S-Shaped curve and is generated by negative feedback on the experience state.

Work Hours

Figure 12 illustrates the part of the SD model capturing the feedback from waiting times to the working hours at the Beatson. The system seeks to set the working hours to a suitable level to cope with the demand on the system. The feedback structure that generates this goal seeking behavior is illustrated in Figure 13 which is taken from Sterman (2000). As the waiting times increase, members of staff tend to work longer hours to fill the gap in capacity. Work hours are constrained by a maximum level, and will reduce when waiting times are within target level.



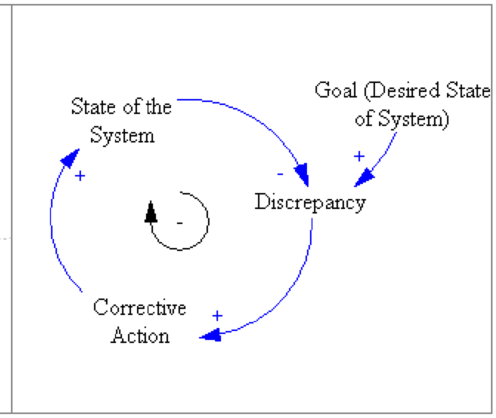


Figure 12: Work hours alter in response to Waiting Times *Figure 13: Goal Seeking Behavior (Sterman 2000)*

Treatment at the Beatson

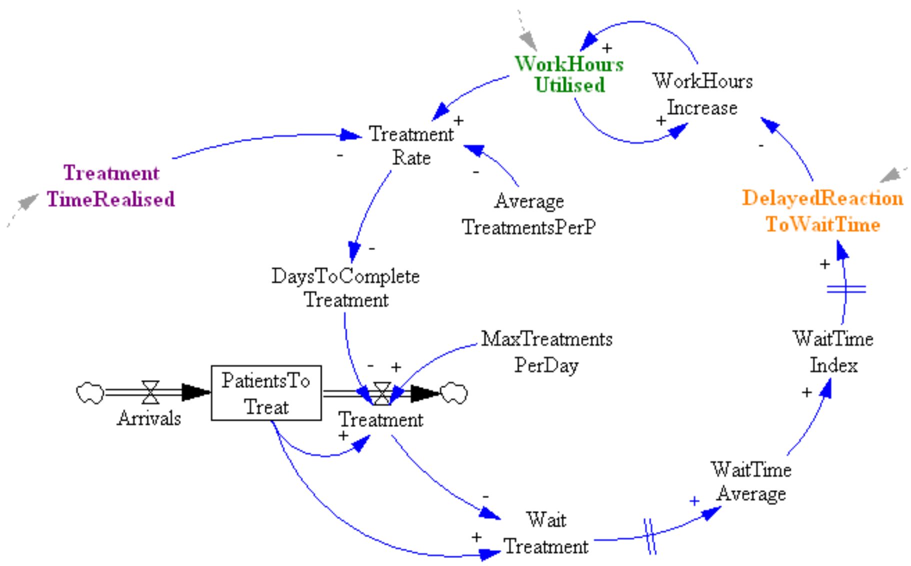


Figure 14: Representing the Beatson Treatment Process

The concepts above then feed into the Treatment Process at the Beatson (Figure 14) to generate the waiting times experienced. Treatment at the Beatson is represented by a single stock (the waiting patients) and a flow (treatment) and applies an average treatment time for all patients. This model represents a significant simplification of the process and as a result is unlikely to capture dynamics realistically or provide value to the client. The next stage of this project is to expand this aspect of the model (to represent the other important phases of the process: booking, scanning and planning) and formally consider the use of a DES model to represent this aspect of the model, and this is discussed in the main body of the paper.