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Development of a Web-based System Dynamics Simulation and Benchmarking Environment for Medical Workforce Planning

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Abstract

The paper presents a web-based modelling and simulation environment which is used for healthcare workforce planning scenario modelling and data benchmarking. Its main aim is to show how modelling and simulation that are based on system dynamics can enhance healthcare user engagement through the use of the World-Wide Web. The presented web-based modelling and simulation environment uses a variety of data inputs and produces a set of data outputs. System dynamics have been used for the realization of the used web-based model. Data benchmarking is performed on the models' outputs. The paper is divided into clear sections which focus on system dynamics and their applications to healthcare, steadily concentrating on the specific web-based simulation environment. It then presents the functionality of the system, its evaluation and a number of conclusions.

Keywords: System Dynamics; Healthcare; Data Benchmarking; Data Mining; ANOVA; Regression; Simulation; Workforce Planning; Modelling

1. Introduction

Workforce planning is a costly process which is characterized by complexity. This complexity is underlined by the large number of people working for the NHS as well as the amount of money provided for training purposes. Furthermore, workforce planning involves not only the clarification of the requirements of the future workforce but also the exact identification of what resources are needed to ensure that workforce considerations integrated with service, activity and financial planning [20]. [19] emphasizes the need for better integration among different types of workforce planning, including the medical workforce planning. The effectiveness of workforce planning in the Healthcare Industry depends on the availability of up-to-date and high-quality data. Data transparency is also considered significant.

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Currently, there are concerns about the validity and the accuracy of collected data. This is enhanced by the fact that medical workforce planning is often undertaken in isolation from strategic and operational planning [4]. System dynamics is a mathematical approach which is based on the use of feedback loops, stocks, flows, and time delays and can describe complex systems. The approach is considered appropriate for the modelling of complex systems and can be used successfully for the modelling of complex healthcare environments. The appropriateness of system dynamics for complex systems modelling can be explained by the capability of the system dynamics models to capture non-linear feedback relationships which characterize the real-world. System dynamics can be used efficiently in healthcare modelling.
The strength of system dynamics, however, is restricted when there is not an efficient way for users to access the model(s) easily and not be able to compare their results. The transfer of the system dynamics models to the web can solve these problems. Furthermore, the creation of a web-based environment in which there will be data import to the web-based model and centralized data export will allow the organized collection of data from different users and the comparison between them. The application of data benchmarking techniques can help the realization of data comparisons. The presented web-based modelling and simulation environment allows users to engage to a process of sharing and comparing data through the quickest and most efficient way which is the World-Wide Web.
The next sections will present in more detail already existing applications of system dynamics in the healthcare industry. A section of the paper is also dedicated on workforce planning in the healthcare industry. This section underlines some critical issues faced currently in medical workforce planning. Furthermore, the paper will present a web-based simulation environment which is currently under development and its operation is based on system dynamics.

2. System Dynamics in Healthcare

System Dynamics has great applicability in Healthcare. Since 2000, there have been attempts to integrate System Dynamics to Healthcare Modelling. [9] proposed the combined use of system dynamics and discrete-event simulation as a hybrid simulation for different modes of governance in the UK healthcare system. In this case, data are exchanged between the system dynamics components of the hybrid model and its discrete-event simulation components. However, depending on how system dynamics and discrete-event simulation represent different aspects of the modelled system, there are three types of collaboration between the two techniques: hierarchical format, process-environment format, and integrated format. The capabilities of each of the two approaches define their role in the hybrid system. [13] suggested another application of system dynamics is on chronic illness management. Chronic illness management is a subject well-suited to system dynamics modelling because of long delays that separate the stages of disease and because of the complex dynamics that affect service delivery. One system dynamics model which was developed for chronic illness management includes a number of stocks (eg. Clinical Care Specialists, CCS patients controlled, CCS referral backlog). Furthermore, the model includes feedback loops. Twenty simulations were performed and three scenarios were tested. In the first scenario, the number of known diabetics remains fixed at baseline values while in the second scenario, one CCS is hired initially but more may be hired as needed. In the third scenario, the budget allows for no more than one CCS [13].
The use of Systems Dynamics Modelling is based on the examination of delays and generally of any problems that may characterize healthcare processes and the monitoring of inter-connected processes among different sub-systems [12], [1]. Systems Dynamics Modelling is also used for the prediction of the behaviour of healthcare systems and the demand for care services [1], [23] as well as for the optimization of system interventions [18], [25]. The purpose of this is the quantification of the impact of change to the healthcare system before real-world implementation. The modelling platform also provided health professionals, stakeholders and decision makers with an accessible visual learning tool that enabled decision makers to develop and test a number of alternative policies.
Health systems are characterized by complex adaptivity. They are characterized by increased complexity in the coordination and collaboration of different groups of stakeholders and the processes associated with them. System dynamics modelling and agent-based modelling are the two most popular mathematical methods for the evaluation of complex systems. The difference between the two methods is that System dynamics modelling is used to study the behaviour of the system at macro-level while agent-based modelling is used to study the behaviour of the system at micro-level. [7] examined a number of System Dynamics Modelling papers. These papers are focused on the optimization of performance-based policies against healthcare productivity and quality of care, the reduction of the total healthcare cost and the reduction of the time of patient admission and treatment. Systems Dynamics Modelling was described as a useful tool for the prediction of future health system behaviour. This is a tool for exploring health policy and the optimization of system interventions. Especially for the improvement of health resources in terms of capacity planning, system dynamics modelling was proved to be very efficient [1], [23]. The provided modelling platform allowed health

professionals, stakeholders and decision makers to access a visual learning environment that allowed the engagement with experts, and this enhanced the development of efficient models [1], [5], [10]. The interface offered by the model allowed users to develop but also test different policies using a framework that corresponded to real-world conditions [22], [2]. Overall, the modelling platform allowed the evaluation of the impact of change to the health system and the identification of possible unwanted system reactions.

The steps for establishing system dynamics models for the analysis of the prevention of chronic diseases include the definition of problem, the development of conceptual and quantitative models, the validation and testing and the policy simulation. During the development of the models, there is continuous acquisition of qualitative and quantitative data that can be used for model optimization. [26] developed a causal loop diagram, a stock-flow diagram and a hybrid diagram using the Vensim PLE software (Ventana Systems, Inc). The development of the causal loop diagram is the first stage of the conceptual model and its purpose is to show the causal relationship among variables. Population and births create a reinforcement feedback loop. Any change on the population has impact to the births and the feedback to the population. A similar feedback loop is created with the population and deaths. The use of the causal loop diagram happens in the initial stage of modelling. The causal loop diagram is the basis for the development of the stock-flow diagram. This diagram describes stock variables, flow variables, auxiliary variables and constant variables. There is establishment of the main relationship between stock variables, flow variables, auxiliary variables and constant variables. The next step is the determination of a non-linear relationship between the variables. The hybrid diagram combines the causal loop diagram with the stock-flow diagram [26].

[17] present how systems dynamics can be used in order to provide more sustainable solutions that will cover the health needs of the people of Thailand. A structured process of group model building was used in order to engage with the different stakeholders and examine patterns of system behaviour and based on these information build a system dynamics model. A series of structured group building model were realised under the guidance of three facilitators. These facilitators had experience on health workforce planning. The outcome of the GMB sessions was the development of a causal-loop diagram (CLD). Examples of the parameters that were analysed during the GMB sessions were the structure of the population of an aging society, the unmet health needs of the population, the utilization of healthcare services in hospital settings and the effectiveness of population health interventions. The hypotheses as depicted on CLD were the basis for the development of a Stock-Flow Diagram (SFD). Three modules (population module, healthcare delivery module, education and labour market module) were built from the CLD in order to represent the mismatches of supplies and demands for the Thai health workforce. Four scenarios were used in order to test the system simulations. Different policies were examined and the potential impacts of each policy for the next two decades (2017-2038) were examined. The use of GMB process allowed the policymakers and stakeholders to understand causal relationships that Thai healthcare systems.

[16] suggest a multi-objective optimization-simulation model for the COVID19's vaccine production, distribution and inventory control management. They proposed a COVID19 Supply Chain Network that includes manufacturers, hospitals, vaccination centers and volunteer students. Vaccine manufacturers send the vaccines to the vaccination centers and to hospitals after their production. Students go to the vaccination centers in order to get vaccinated. The model assumes that vaccination centers operate in limited capacity as social distancing must be followed even after the injection has been received. The input parameters of the model are the values of the initial population, the duration of the disease, the transmission rate and the average death rate. Examples of output parameters are the number of healthy students, the number of infected students, the number of deaths and the number of recovered students. There was utilization of various optimization approaches such as the Bounded Objective Function (BOF) as well as of the variable neighborhood search (VNS) algorithm and of the whale optimization algorithm (WOA). A new heuristic method known as the modified WOA (MVWOA) was developed in order to solve the problem under different sized conditions [16].

[11] show how system dynamics can be applied in emergency care for older people. The parameters of the model were extracted from a linked data analysis of healthcare data related to the Yorkshire and Humber region of the United Kingdom. The CUREd database which includes healthcare data for a large portion of the UK population was used. The database allows the tracking of patients from their initial emergency call, their Emergency Department (ED) attendance, their ED discharge or hospital admission. Additional data sources include the Office of National Statistics (ONS) mortality statistics and the number of care home residents in the Yorkshire & Humber region as produced by the Care homes market study. A System Dynamics model was developed as a decision support tool for emergency care service planners. The model and its user interface were developed in the simulation software AnyLogic (version 8.7.3). The model runs two scenarios: a baseline scenario and an intervention one. The results include a number of key hospital metrics such as the average number of patients admitted to the Emergency Department. The results are shown as graphs and each graph displays a selected metric over the duration of a specific time period under the baseline scenario compared with the selected intervention scenario [11].

3. UK Workforce Medical Planning – Current Situation & Problems

Medical Workforce Planning is a costly and complex process, and this is shown by the amount of money that is provided for training as well as the number of people who work in healthcare organizations. In addition, workforce planning must support the National Health Service in such a way so that productivity is met while at the same time there is effective coordination with service and financial planning. The complexity of medical workforce planning is related to a number of activities such as the introduction of new clinical roles, the re-distribution of staff responsibilities and the negotiation of contracts. A number of other issues are also considered in the planning of medical workforce. These are the provision of training requirements and demographic, technological, and policy updates. These issues are very important as they define how the future supply and demand are matched in a way that the number and type of staff to be recruited, the nature of training to be realised, and the amount and type of workforce development activities are not compromised.

Effective workforce planning in the NHS depends on the availability of up-to-date, high-quality data. Thus, workforce intelligence is very significant. For example, the Centre for Workforce Intelligence (CfWI) used to provide data intelligence in contrast to the NHS Information Centre which is only a data warehouse [14]. Furthermore, there is the need for data transparency. This can be achieved through the enhancement of the engagement of workforce planners and commissioners with clinicians and others responsible for service re-design. The reason for better data transparency lies on the fact that workforce planning is not only the determination of the requirements of future workforce but also how these requirements will affect service and financial planning. The provision of quality data will allow better integration of the different services of care and support.

The modelling of medical workforce planning is a very challenging process. This is because there are many factors that can shape workforce planning in the health sector. For example, the constant change of public health priorities, the focus on the prevention of chronic diseases and the increasing level of complexity and fragmentation of the healthcare system are such factors [15]. Examples of other parameters that could be considered are population requirements for services, and workforce supply and productivity. There are a number of data sources that can provide data to healthcare modellers. The NHS Information Centre in the past and currently the NHS Health and Social Care Information Centre provide a large collection of datasets as well as the UK Department of Health which has a large collection of publications. Much of the data required for this modelling is, however, collected and analysed at a local level where healthcare modellers have direct face-to-face meetings with people from healthcare during which they evaluate the requirements of the modelled system. However, it is possible that during these meetings, not all the necessary data are provided or because of miscommunication, there are different perceptions from the involved parties about the way the examined system should be modelled.

There is a clear benefit from consistency in data collection, and of being able to access this data from a central point which would allow easy and continuous access to good quality data. Furthermore, the nature of these data should be dynamic, thus they should be re-evaluated periodically. This evaluation is important as it can test the validity of data. The paper presents a web-based simulation environment which allows users of different Information Technology backgrounds but with experience in the Healthcare Industry to use different datasets in an online simulation environment so that they can produce a range of scenarios. Their input data and the produced model outputs can be saved in an online storage location so that they can be compared with produced outcomes from other users' use of the online model.

4. Modelling for Healthcare Workforce Planning

There are a number of models currently used for medical workforce planning. An example of such a model is the Child and Adolescent Mental Health Services (CAMHS) Integrated Workforce Planning Tool. The model allows the creation of a workforce plan for an area, the engagement of partners in the planning process, and the collection and analysis of data. In addition, it is designed to enhance workforce planning capacity and capability across organizations [21].

The Centre for Workforce Intelligence (CfWI) had used modelling for medical workforce planning. This modelling was based on four directions: Horizon Scanning, Scenario Generation, Workforce Modelling, and Policy Analysis. Horizon Scanning refers to the possible parameters that can affect medical workforce planning. Scenario Generation refers to different scenarios about how the future of medical workforce planning could be. Workforce Modelling estimates supply and demand for the generated scenarios while Policy Analysis identifies which policies are the most effective across the specified range of scenarios [8].

The UK Department of Health has developed a range of tools for the pathology, physiological sciences, and physical science and engineering workforce. The NHS and SIMUL8 have jointly developed a healthcare scenario generator. It is a healthcare modelling tool to simulate health and social care systems. It comes with pre-defined population and prevalence data, and with a number of generic pathways of care. Users can simulate healthcare activity for one to 10 years or more. The results include workforce capacity, flow, and cost [24].

Whole Systems Partnership (WSP) has developed a range of healthcare models using appropriate Systems Dynamics software. Examples of such models are the Medical Workforce Planning (MWP) model, the Dementia model, and the Reablement model. The Medical Workforce Planning (MWP) model simulates characteristics of the local medical workforce, the commissioning activity for local training and the potential requirements for commissioning future training activity. The model is the basis for the development of a framework for discussion between strategic partners about the implications and the alternatives in the development of long-term commissioning plans for a medical workforce. The medical workforce modelling tools are used by members of the Workforce Modelling Collaborative and specifically local education and training boards who collaborate with local Deaneries in order to enhance the engagement of partners in the re-shaping of the medical workforce strategy. The models have as a purpose to identify the impact of the changing workforce based on age and gender, identify the number of training places that are needed in order to face the projected demand, identify the number of trainees that have completed their training each year and provide an estimate of the trainees who are not able to find an appointment [27].

5. The Whole Systems Partnership Medical Workforce Planning Model

Whole Systems Partnership (WSP) has developed a range of healthcare models using appropriate Systems Dynamics software. Examples of such models are the Medical Workforce Planning (MWP) model, the Dementia model, and the Reablement model. The MWP model uses characteristics of the local medical workforce and of the commissioning activity for local training and processes data related to the requirements for commissioning future training. The medical workforce modelling tools are used by members of the Workforce Modelling Collaborative for the purpose of better re-shaping of the medical workforce strategy. Examples of parameters that the MWP models considers is the number of trainees that complete training each year, the number of posts that will be required following retirement, the number of training posts that need to be commissioned per year and the number of trainees that are not able to find an appointment [27].

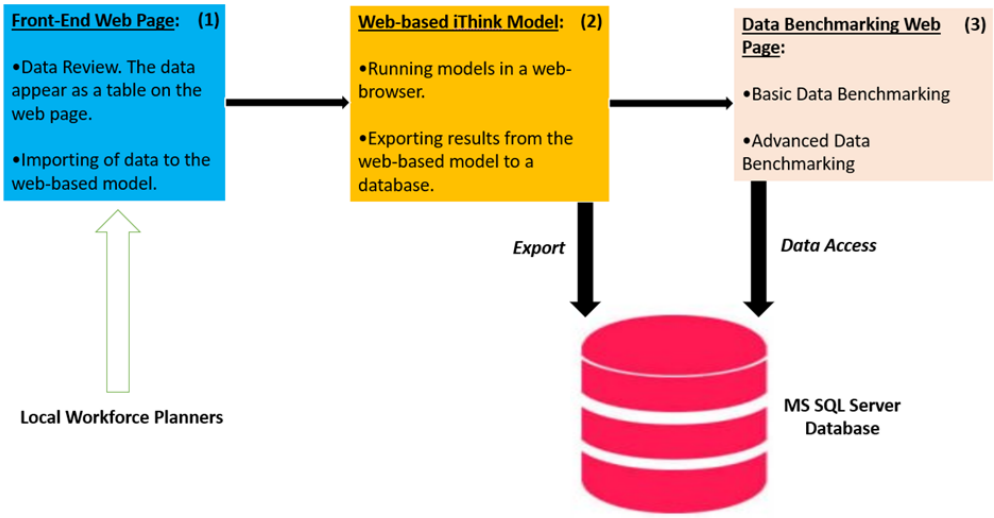
6. The Web-based System Dynamics Modelling & Simulation Environment

The functionality of the web-based System Dynamics Modelling and Simulation environment is based on three main directions. The first direction ((1) in Fig.1) is the Data Review and Insertion to the Web-based Model. In this case, the users are capable of reviewing different datasets, modify them and feed them to the model. This has the benefit of securing local ownership of data whilst also ensuring consistency of the data definition. The second direction is the running of the model in a web-browser. The users are capable of running a simulation model that runs on a web browser. The next direction (2) is the production of model outputs and export of data to a centralized storage location. The users in this case run the web-based model and data are saved as time-stamped datasets. The final direction (3) is Data Benchmarking which includes the comparison of the produced model data of a user with the produced model data of other users or past data using a number of techniques that are presented in the next sections of the paper.

The overall architecture of the web-based modelling and simulation environment can be seen in Figure 1.

The Whole Systems Partnership model that was used is built using the iThink software provided by isee systems. iThink software is a systems dynamics modelling and simulation software. It offers to the user a number of capabilities such as the creation of stock and flow and causal diagrams. There are built-in mathematical functions while the users can insert their own equations to their models. Input devices include ‘sliders’, ‘switches’, ‘graphical input devices’ and the outputs of the model are provided in a graphical and numerical way. A model can be published to the World-Wide Web using the isee NetSim Server or a model can be exported and hosted to a web hosting service. One of the core elements of the developed environment is a C# handler which is a program that communicates with the web-based healthcare model and extracts specific information from it in the form of a JavaScript Object Notation (JSON) string. This is how the data associated with a model are exported to the Microsoft SQL Server database. Other core elements are the models that have been provided by the Whole Systems Partnership (WSP). A Python-built dashboard is connected to the Microsoft SQL Server database so that different analyses of the data (data benchmarking) included to the database can be performed using the different Python packages and methods. Examples of such packages are scikit-learn, pandas and researchpy.

Fig. 1: Architecture of the Web-based System Dynamics Modelling & Simulation Environment



7. Data Benchmarking

The term 'Benchmarking' refers to the evaluation of a certain practice with another practice which has been set as a standard of excellence. Benchmarking was introduced by the Xerox Corporation in 1979; however the Japanese would try to use benchmarking long before Xerox. [6] provides a very good definition of the term 'Benchmarking'. Specifically, benchmarking is the continuous process of product, service and practice measurement against leading product, services and practices in order to identify the best ways that result to improvements in performance [6]. It is therefore much more than simply comparing numerical outputs from a data collecting exercise. Benchmarking can be seen as a procedure that sets directions by managing the relations between policy developments, clinical pathways, and processes. The advantages of benchmarking for the Healthcare Industry are the setting of limitations under a realistic context and the prevention of waste of resources. Furthermore, benchmarking allows healthcare organizations to measure their services in terms of results that are important to users and creates the appropriate requirements for the comprehension of the dynamics and practices of good health service performance [3].
By considering the level of user-friendliness that the web-based modelling and simulation environment should provide, the data benchmarking techniques which are used have been classified as follows:

7.1 Basic Data Benchmarking

7.1.1 Calculation of the deviations of the datasets produced during each running of the web-based model. The standard deviation shows the dispersion of the data.
7.1.2 Calculation of the mean values of each produced outcome of the model and comparison with the mean values produced by other users. The importance of the calculation of the mean value is to understand the central tendency of the data.
7.1.3 Comparison of the produced model run outputs with data provided by the UK National Health Service (NHS).

7.2 Advanced Data Benchmarking

7.2.1 Application of Data Clustering to find hidden relations among produced model outcomes. Data clustering can be applied to the data that are produced by the different users each time they run the web-based model in order to identify data proximity with selected data points.

7.2.2 Application of Linear Regression to identify possible linear relationships among data and perform data forecasting. The linear regression is used in order to identify whether there is linear connection between the produced model output and the parameters which affect this output. If there is such a connection, then the linear regression algorithms does data prediction based on the linear relationship. Scikit-learn has been used to develop regression models for prediction of future medical workforce demand based on demographic changes.

7.2.3 Analysis of Variance (ANOVA) in order to evaluate the impact of different variables to the models' outputs. The use of ANOVA allows the identification of the impact of different factors in the medical workforce planning process.

7.2.4 Linear Programming: this is achieved through Python PuLP which is a Python package for modelling linear optimization problems. In the case of medical workforce planning, it can help identifying the optimal allocation of medical workforce.

7.2.5 Data Analysis and Visualization: Specific Python libraries such as Pandas and NumPy have been used for the purpose of data handling and analysis and for numerical operations. Matplotlib has been used for the visualization of medical workforce trends.

8. Deployment of the Healthcare Workforce Planning Model

A prototype of the presented web-based modelling and simulation system was presented at a Healthcare event in London. The iThink model that was used was the Radiology model which is used to calculate the training posts for Radiology. The event involved 20 people from 8 different regions of the United Kingdom. The presentation and testing included the following steps:

A. Provision to people of the same model but with different baseline assumptions.
B. Exploration of the off-line version of the model and development of final decisions as to how many training places to commission over coming years in order to balance demand.
C. Use of the online version of the model and replication of the decisions in that model before each run.
D. Acquisition of the model outputs to an online storage location.
E. Comparison of the model outputs based on the initial decisions.

9. Reflections

The development of the presented web-based modelling and simulation environment underlines the need for enhanced user friendliness. The environment targets mainly users of different computing backgrounds and with probably limited statistical knowledge; therefore, it classifies the data benchmarking techniques to compulsory and optional. The way the information is displayed affects the users' interaction with the web-based environment. Considerations as to how the users will finally interact with the web-based modelling and simulation environment are challenging. The centralized storage location of model outputs also offers the capability to modellers and users to compare data trends, however there may be issues related to whether a user is willing to offer their own data in order to be benchmarked. Furthermore, the use of the presented system is a proof of the necessity of using data mining/data benchmarking tools in NHS operations. Data Benchmarking is important for NHS operations as it can help extract useful data that will help healthcare providers in the provision of high-quality health services and the further reduction of health inequalities. Moreover, the use of Data Benchmarking can help in the development of collaborative platforms among different NHS organizations that will help the easier and more efficient exchange of information as well as the development of innovative scenarios in relation to the optimization of the performance of different NHS operations and the forecasting of possible challenges and risks. The contribution of the presented environment is the clear integration of system dynamics tools with a web-based platform that hosts them and the extraction and analysis of useful information from the developed models.

10. Conclusions

System Dynamics can help significantly in the analysis of complex processes that characterize the Healthcare Industry.

Because of the complexity of the UK National Health System, it is crucial that information is shared in a quick and efficient way so that better decision-making is realized. Currently, the level of automation in information sharing is not such that it allows the quick data exchange, review and benchmarking especially in large organizations, such as the NHS. The presented web-based modelling and simulation system presents an innovative way for users to apply different scenarios based on different datasets and using an online centralized storage system to compare these results with the results of other users. As a result, the users are able to test the strength of different scenarios and compare their data with the data of other users. For the modellers, the web-based modelling and simulation environment can provide a better insight into the current data trends preferred by the users. Furthermore, the collected data can be used for better decision-making. It is important to underline the significance of the role of the C# Handler in the extraction of data from the web-based models. The data benchmarking capabilities of the developed system would not be possible without the extraction of data from the web-based model. It is also important to underline the significance of bringing on a web-based platform concepts and tools related to System Dynamics. This can act as the basis for brining other simulation and modelling theories on the web and integrating them with data mining and benchmarking tools.

In terms of user engagement, the presented web-based modelling and simulation environments allows the real-time collection of data from numerous users. The provision of healthcare models through the web offers constant availability of modelling and simulation capabilities. The centralized storage of data with details about the specific time and date of data production allows their benchmarking in an organized way while the users can keep track of past results. Trends can be easily formed based on past data and forecasting can be realized. For the users, data benchmarking allows the re-evaluation of their scenarios while for the modellers, it allows better use of system dynamics for model creation. Overall, the presented system is a web-based integrated platform that combines the capabilities of System Dynamics models with data analysis tools. Different models based on different scenarios can be developed through the web platform allowing for a variety of data to be extracted and analyzed. This creates a large pool of data that allows better decision-making related to different aspects of the operations of NHS or any other healthcare institution. It also shows the importance of integrating different technologies on the World-Wide Web in relation to data exchange and handling.

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