Framework to support personalized learning in complex systems

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Purpose – Numerous studies document that students struggle to comprehend complex dynamic systems (CDS). This paper describes a design framework applied to the creation of a personalized and adaptive online interactive learning environment (OILE) to support students in their study of CDS.

Design/methodology/approach – A holistic instructional design is applied in five steps to create the OILE. The OILE has the following characteristics: A) It presents a complex, dynamic problem that learners should address in its entirety. It then allows learners to progress through a sequence of learning tasks from easy to complex. B) After completion of each learning task, the OILE provides learners with supportive information based on their individual performance. The support fades away as learners gain expertise. C) The OILE tracks and collects information on learners' progress and generates learning analytics. The OILE was tested on 57 system dynamics students.

Findings – This paper provides evidence that supports the theoretical design framework from the literature. It also provides a sample from students' progress logs to demonstrate how the OILE practically facilitated students' cognitive development. In addition, it provides empirical evidence regarding students' attitudes towards the OILE that was obtained from administering two questionnaires.

Originality/value – In light of supportive evidence from the literature, students' progress in the cognitive domain, and confirmative response in the affective domain, the use of personalized and adaptive OILE to support learning about CDS is considered promising.

Keywords: Personalized learning, Adaptive learning, System dynamics, Systems thinking, Learning environment, Learning analytics
Article Type: Research Paper

1. Introduction

Decision-makers and people in general face a wide range of increasingly complex, dynamic problems in both the public and private sectors (Sterman, 1994; Davidsen, 1996; Jonassen, 1997; Barlas, 2007; Greiff et al., 2012). These problems have a dynamic nature (change over time) and they commonly originate from the internal structure of the system that generates the problem (Diehl and Sterman, 1995; Davidsen, 1996). Structure is the cause and effect relationship among variables that define the system. Numerous studies document that people have difficulties comprehending complex, dynamic systems (CDS) and managing these systems effectively (Dörner, 1996; Moxnes, 1998, 2004; Cronin et al., 2009).

Moxnes & Saysel (2009), in their research about misperceptions of global climate change, show that people have cognitive difficulties with building appropriate mental models unless they are supported by proper strategies. Other studies on renewable resource management (Moxnes, 1998, 2004; Jensen, 2005) and on global warming (Sterman and Sweeney, 2007) have confirmed the problem.

The difficulty in understanding CDS arises from lack of three different types of capabilities: 1) cognitive capability to comprehend structural complexity; 2) skills to infer the dynamic behavior of a system from its underlying structures; and 3) effectiveness of methods, techniques and tools that are available to analyze systems (Davidsen, 1996; Spector and Anderson, 2000; Jonassen, 2000; Ifenthaler and Eseryel, 2013; Van Merriënboer and Kirschner, 2017).

The objective of this paper is to develop a framework that identifies educational methods that consist of a well-composed set of instructional techniques and tools. The techniques are manifested in the form of educational tools. The tools are those created to materialize the instructional techniques that support students in their study of CDS.

The paper describes a design framework applied to the creation of a personalized and adaptive online interactive learning environment (OILE) to support students' learning. Often the terms "personalized learning" and "adaptive learning" are used in similar educational contexts, referring to "the tailoring of education to learners' current situation, characteristics, and needs" (Graf & Kinshuk, 2012, p. 2592). However, each term has its own specific definition and focus area. The US Department of Education (2017) defines personalized learning as "an instruction in which the pace of learning and instructional approach are optimized for the needs of each learner" (p. 9). Graf & Kinshuk (2012) share a similar essence in their definition of personalized learning – "tailoring education to learners' current situation, characteristics, and needs in order to help them to achieve the best possible learning progress and outcomes" (p. 2592). Here, the focus is more on "the consideration of the learner as an individual person". On the other hand, the focus in adaptive learning is on "the aspect of achieving the tailoring automatically (typically by a learning system)". Bilic (2015) defined adaptive learning as the "adjustment of one or more of the characteristics of a learning environment" to match the needs of learners. The adjustments can be on how the learning tasks are presented, on how they are sequenced depending on the learners' progress, and on how supportive information is provided. While adaptive learning can also be applied to groups of learners – adjusting the learning environment to those groups, personalized learning always "focuses on the individuals, regardless of the fact whether they work alone or in groups" (Graf & Kinshuk, 2012, p.2592).

Personalized and adaptive OILEs are important to students of educational programs that employ system-thinking concepts. Courses offered in such educational programs are interdisciplinary and often breakdown the barriers among fields such as natural science, engineering, political science, economics, and medicine. Furthermore, students who register for such programs often come with diverse academic and cultural backgrounds and experiential perspectives. Such issues create practical difficulties for educators when trying to bring the students to the same level and help them proceed at an equal pace. This is because:

1) Individual students are unique and have unique learning paths.
2) Educators in schools and universities seldom educate their students to be "problem solvers to solve problems that emerge from their disciplines". Rather they teach them about the disciplines. Students are taught about "sociology, psychology, history, biology" not "how to be a sociologist, psychologist, historian, or biologist" (Jonassen, 2010, p. xxi).
3) Some students are very shy to come forward and ask for help either from their teachers or from their colleagues due to cultural and experiential perspectives. It is difficult for a teacher to identify

students who are struggling with their learning material unless either the students go to the teacher on their own or exam results are published.

However, personalized and adaptive OILEs can support students while studying CDS in their own time and their own pace. In addition, they can help to minimize gaps that exist among students by providing computer-mediated resources based on the unique needs of learners. Furthermore, they provide predictive learning analytics to the teachers about the progress of each student. They also help teachers and instructional designers to identify learning materials and learning tasks that need revision to improve the quality of the teaching/learning.

2. Research Questions

This paper aims to demonstrate how the OILE could be designed to support individual students in their study of CDS. In particular, the following three research questions were investigated:

1. How can one address the cognitive challenges associated with the teaching/learning of CDS?
2. Can personalized and adaptive OILE facilitate students' cognitive development in their study of CDS?
3. Can personalized and adaptive OILE support students' affective domains of learning in their study of CDS?

3. Characteristics of the OILE

This section of the paper describes the characteristics of the OILE created to address the challenges associated with the teaching/learning of CDS. The OILE has the following three predominant characteristics:

A. It presents an authentic, complex, dynamic problem that the learner should address in its entirety. It then proceeds to allow learners progress through a sequence of learning tasks from easy to complex.

B. When solving the problem, learners interact with the OILE. After completion of each learning task, the OILE provides learners with supportive information based on their individual performance. The support fades away as learners gain expertise.

C. It tracks and collects information on students' progress and generates learning analytics, which are used to assess the students' learning.

The figures below show sample screenshots associated with the characteristics offered by the OILE. Figure 1 is a sample screenshot from the OILE's welcome page and Figure 2 is a sample screenshot from item description page. The arrows in Figure 2 indicate the components of an item description page (detailed explanation is given in section 4.5 – tools and interface).

Figure 3 represents a learning path of a student who has worked on the OILE from question number "Q1-1" to "Q2-10". The green lines represent progress in performance and the red lines represent movement to remedial questions. Detailed discussions on learning paths in the context of this paper are given in Section 4.4 and Section 5.1.

Designing interactive learning environments that effectively support learning in and about CDS is a challenging but fascinating task, which requires the synthesis of different instructional methods, techniques and tools (Sterman, 1994; Davidsen, 2000; Eseryel et al., 2011). Because these learning environments are required to influence the formation of mental models that govern learners' decision-making and action in CDS (Davidsen, 2000). Moreover, the learning environments are required to provide contexts to practice scientific methods in both virtual and real worlds, while facilitating the practice (Sterman, 1994). A review of the literature in the area of supporting learning in and about CDS show but a few interactive learning environments that have been designed to offer such a comprehensive support.

Most of the interactive learning environments designed to foster learning in and about CDS are ready made black-box simulators with user-friendly interfaces that display the surface relationship between input provided by the user and output provided by the simulation engine (Alessi, 2000; Pavlov et al., 2015). Such learning environments provide little or no information about the internal structure of the CDS. They provide platforms

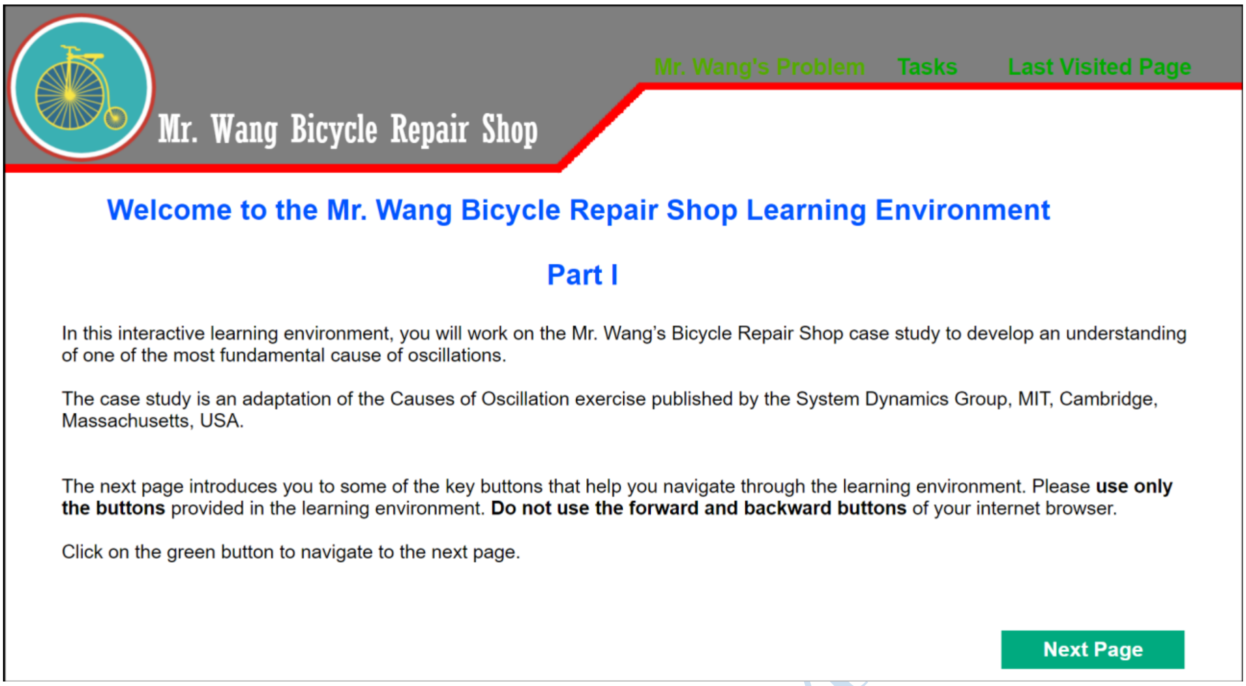


Figure 1. Sample welcome page

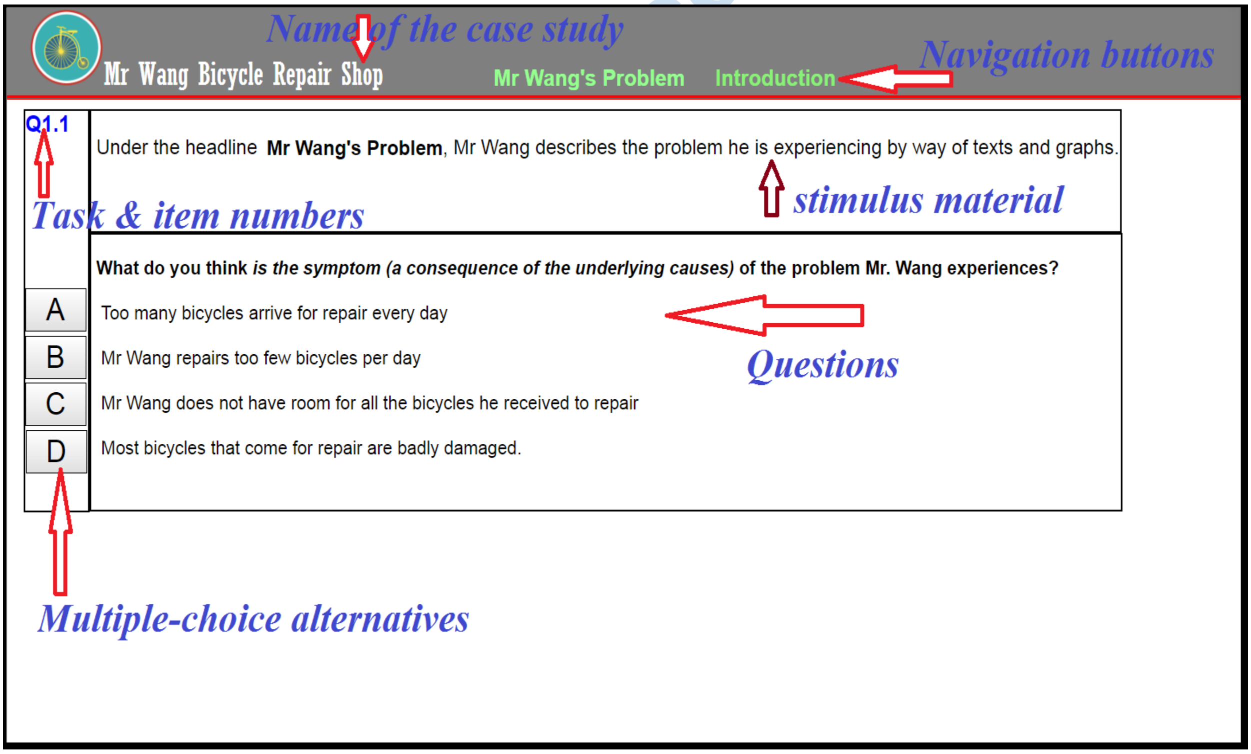
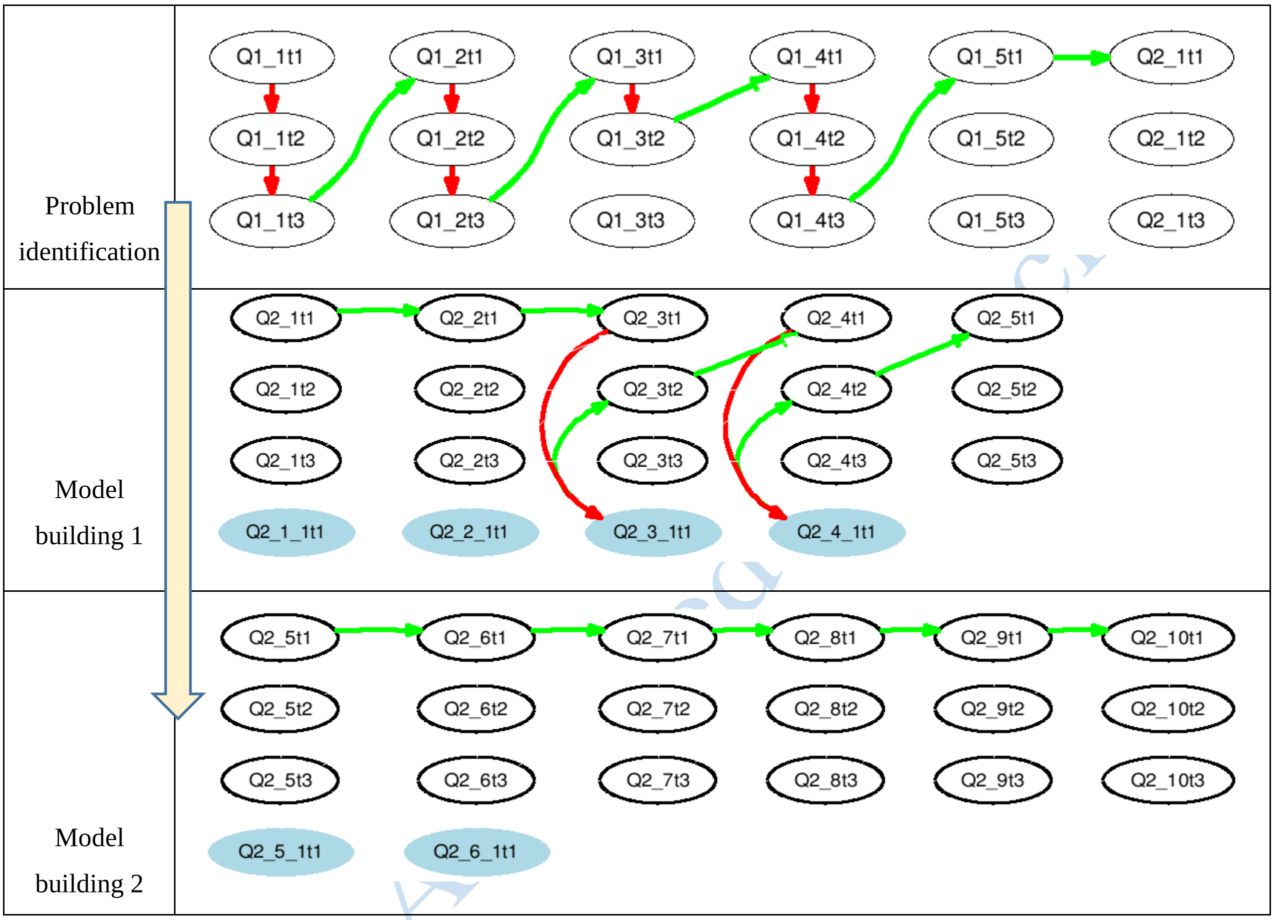


Figure 2. Sample item description page

either to conduct controlled experiments (trails and occasional success) as in the case of management flight simulators or to train learners with specific tasks/procedures, for example driving a car or flying an aircraft without diving into the inner workings of the devices (Sterman, 1994; Alessi, 2000; Pavlov et al., 2015). Moreover, these learning environments do not require learners to pass through rigorous scientific methods such as problem identification, hypothesis formulation, analyses and interpretation of results. On the other hand, there are few other interactive learning environments that have been designed to promote discovery learning, where learners are engaged in a scientific inquiry to uncover the underlying structure of CDS and solve their associated problems (Alessi, 2000). However, what is often missing in these kind of learning platforms is an effective learning support that facilitate the students' learning. Even if there are support mechanism in these platforms, often this support has been designed to fit the so-called average learners without accounting for strugglers and/or top performers.



Notes: The green lines represent progress in performance and the red lines represent movement to remedial questions; the yellow arrow indicates the tasks sequence

Figure 3. Sample learning path of a student

That said, there are system dynamics based interactive learning platforms designed and implemented in Forio Simulate (forio.com) for courses offered at Sloan School of Management (see Sterman, 2014a, 2014b) and at a number of other major US universities. These learning environments have been designed to offer support to learners that study key concepts in strategic management, system dynamics and related fields. They use real world case studies and allow students to carry out experiments using simulation models so as to gain experience with complex systems. With the help of their user-friendly interfaces, learners have the capability to alter the various settings of the simulation, make decision using input devices and explore the consequences of their decisions. However, these platforms do not offer support for students to (re)create the simulation models that represent the structure of the underlying CDS. They also do not provide thorough and comprehensive support to individual students, at each stage of the learning process, to help them uncover the relationship between the underling structure of each CDS and its development over time (i.e the relationship between structure and behavior). Often debriefings are provided merely towards the end of the learning process.

The design framework proposed in this paper, however, aims at incorporating these elements of learning that are missing from the learning process. This framework allows learners to be engaged in a scientific discovery practice to address authentic learning tasks, uncovering the relationship between structure and behavior of CDS. The OILE provides intermittent scaffolding to support learners based on their individual performance so as to inform the development of both their mental models and the formal models they would create. The scaffold fades away as learners gain expertise. It also collects learning analytics using built-in trackers to inform both teachers and students regarding the learning progress and allow for the redesign of the instruction when needed.

The section below presents the framework used to design the OILE as well as the underlying instructional design theories, where the three characteristics of the OILE are distilled out. It then presents the instructional method as well as the instructional techniques employed in the design of the OILE to support students' learning. Finally, the section presents the organization of the learning tasks in the OILE.

4. A five-step design framework for the OILE

The OILE is designed under the guidance of a five-step design framework listed below.

1. Identify instructional design models
2. Identify authentic (real world) learning tasks
3. Identify instructional methods
4. Identify instructional techniques
5. Design interface and implement the tool

Table 1 summarizes the five steps involved in the design of the OILE. And the subsections below give a detailed account of the five steps. The analyses presented under these five steps give a literature based theoretical foundation to the OILE development and answer the first two questions of the research:

- How can one address the cognitive challenges associated with the teaching/learning of CDS?
- Can personalized and adaptive OILE facilitate students' cognitive development in their study of CDS?

4.1 Identify instructional design models for the teaching/learning of CDS

The systems thinking approach is, *the whole is always more than the sum of its parts*, indicating that the structure of parts synergizes to produce the resulting dynamics of a system. Hence, the instructional design models considered in the design of the OILE should foster this holistic perspective.

Van Merriënboer and Kirschner (2017) argue there are three common problems that instructional designers should address when designing instructional models that support learning in and about complex systems, "compartmentalization of knowledge, skills and attitudes; fragmentation of what is learned in small, incomplete or isolated parts; and the transfer paradox" (p.13). They, however, claim instructional design models that follow the holistic perspective can solve these problems by integrating the different domains of learning into a unit of instruction and by facilitating the development of an integrated knowledge base that increases the chance of transfer. Spector (2000) also noted the above-mentioned problems and proposed a set of five basic principles that complements the holistic instructional perspective, to consider during instructional design (p.524):

- Learning Principle (L) - learning is fundamentally about change.
- Experience Principle (E) - experience is the starting point for understanding.
- Context Principle (C) - context determines meaning.
- Integration Principle (I) - relevant contexts are broad and multi-faceted.
- Uncertainty Principle (U) - we know less than we are inclined to believe.

This study utilized these five basic principles and the holistic perspective as inclusion criteria for choosing instructional design models that informed the creation of the OILE.

The first column of Table 1 shows the six instructional design models that met the inclusion criteria and that have influenced the development of the OILE: the 4C/ID, First Principles of Instruction, CLE, TCI, Cognitive Apprenticeship, and Elaboration Theory.

The primary emphasis in learning environment design varies across the six models. Nevertheless, the models have four key features that make them suitable for the design of learning environments intended to foster understandings of CDS.

Table 1. A five-step design framework for the OILE

<table>
<tr><th colspan="2">Identify instructional design models</th><th>Identify authentic learning tasks</th><th colspan="2">Identify instructional methods</th><th>Identify instructional techniques</th><th>Design interface and implement the tool</th></tr>
<tr><td rowspan="6">Holistic Instructional design</td><td>The Four Component Instructional Design model (4C/ID, Van Merriënboer and Kirschner, 2017)</td><td rowspan="6">Causes of Oscillation: Mr. Wang Bicycle Repair Shop Case Study</td><td rowspan="6">Scaffolding Instructional Method (Wood et al., 1976; Belland 2017)</td><td rowspan="2">Dynamic assessment</td><td rowspan="2">Multiple-choice questions and Open-end questions</td><td rowspan="6">- Welcome page
- Learning task presentation page
- Supportive information provision page
- Navigation buttons (OECD, 2013; Alessi and Trollip, 2001)</td></tr>
<tr><td>First Principles of Instruction (Merrill, 2002, 2013)</td></tr>
<tr><td>Constructivist Learning Environments (CLE, Jonassen, 1999)</td><td rowspan="2">Providing just the right amount of support</td><td rowspan="2">- Story telling: linking previous and current learning tasks
- Repeated trial: giving multiple opportunities to try a question
- Providing feedback and feed-forward
- Item branching: branching to either a simpler or more complex concept
(Jonassen, 1999; Reigeluth et al., 2017; Van Merriënboer and Kirschner 2017; Merrill, 2013)</td></tr>
<tr><td>Task Centered Instruction (TCI, Francom and Gardner, 2014; Francom 2017)</td></tr>
<tr><td>Cognitive Apprenticeship (Collins et al., 1989; Collins et al., 1991)</td><td rowspan="2">Intersubjectivity</td><td rowspan="2">- Providing part-task practice (Van Merriënboer and Kirschner, 2017)
- Providing summary</td></tr>
<tr><td>Elaboration Theory (Reigeluth, 1999).</td></tr>
</table>

First, they offer a unifying perspective regarding learning tasks. These instructional design models argue that the learning tasks should;

- be at the center of the instructional design
- be based on authentic problems
- comprise the entire knowledge and skills that learners would be able to acquire when they complete the entire learning tasks
- be designed in a way that learners can address the authentic problem in its entirety, from "start to finish, rather than discrete pieces" of the problem
- be designed in a way that learners can progress from simple to complex steps in their analysis of the entire task

These core principles constitute the foundation of the first characteristic of the OILE (Section 3) – the OILE first presents an authentic, complex dynamic problem then allows learners to progress from simple to complex steps in their analysis of the entire problem.

Second, the instructional design models underscore the importance of providing instructional scaffolding that gradually fades away over time as learners gain expertise. The authors of the six instructional design models argue that learners should receive the right support at the right time. The support bridges possible learning gaps and sustains students' engagement with their learning tasks. This principle serves in part as a base for the second characteristic of the OILE – designing supportive information that fades away, and partly as a base for the third characteristic of the OILE – the collection of process log information to evaluate the status of the learners.

Third, they all promote holistic instructional design. They recognize the dynamic interdependency between the elements that constitute an instructional system of complex learning that makes the instructional system an irreducible whole (Van Merriënboer and Kirschner, 2017). For example, an analysis of the performance of a learner regarding a certain learning task is used to design the supportive information presented to the learner. This information is then used as an input to design the next task. However, the level of difficulty of the next task is determined based on the learner's performance while addressing the previous task. The learner can subsequently progress either to more complex or to a simpler learning task. This key principle served as a foundation to all of the three characteristics of the OILE.

Fourth, they emphasize the importance of transfer of knowledge and skills to everyday life. The tasks the learners undertake as part of the learning experience and the instruction they follow in the learning environment should help the learners transfer their knowledge and skills to related real world settings. This last principle is also integrated into all of the three characteristics of the OILE.

4.2 Identify authentic learning tasks

The above-mentioned six instructional design models require authentic learning tasks to be presented to learners, and so does the design framework of the OILE.

An authentic, complex and dynamic problem has been identified during the design of the OILE. The learning task is a case study to be completed by master students in the system dynamics program at the University of Bergen, Norway. The case study is about Mr. Wang's Bicycle Repair shop, aimed at teaching the students about the causes of oscillation.

Oscillation is one of the fundamental modes of behavior produced by non-linear feedback systems. It occurs in virtually all business areas such as in commodity markets, labor supply chains, manufacturing supply chains, and the real estate market. Using this case study, the students investigate the causes of oscillation in the backlog of the Bicycle Repair shop. In this study, backlog represents the bicycles that have been delivered to the company and that are in need of repair.

The content of the learning environment has been reorganized based on the recommendation of "best practices in modeling" by Martinez-Moyano and Richardson's (2013) and Richardson's (2014a, 2014b, 2014c) "canonical sequence" framework that help to lead learners seamlessly from problem identification and conceptualization to model testing and evaluation. The objectives at each stage of the learning and the intended learning outcomes were formulated with the help of frameworks provided by Munoz and Pepper (2016) and Schaffernicht and Groesser (2016).

The Mr. Wang case study is divided into five tasks. A task is a subset of challenges with specific objectives that students should be able to achieve upon completion of that task. The first task of the case study focuses on problem identification and definition. The learners are required to identify the problem the repair shop has. Tasks 2 to 5 concentrate on hypothesis formulation and analysis of that hypothesis. The students are required to formulate a hypothesis about the underlying causal structure of the problem. They then proceed to analyze the relationship between that structure and the consequent dynamic behavior by building computer models. The students carry out this task in a reiterative process until they arrive at a structure that best explains the identified problem. The complexity of the underlying causal structure and its analysis increases as students progress from Task 2 to task 5.

4.3 Identify an instruction method

Scaffolding is the main instructional method applied in the design of the OILE. Wood et al. (1976) defined scaffolding as a "process that enables a child or novice to solve a problem, carry out a task or achieve a goal which would be beyond his unassisted efforts" (p. 90). The support provided is "meant to extend students' current abilities" so that they can carry out the "bulk of the work required to solve the problem" (Belland 2017, p.17).

The scaffolding instructional method comprises three elements: dynamic assessment, provision of just the right amount of support, and intersubjectivity (Belland, 2017). Dynamic assessment and provision of just the right support are interrelated and must be carried out iteratively (Belland 2017). The dynamic assessment determines whether the learners are constructing knowledge and skills from the learning tasks and whether they are on the right path to be able to perform the tasks independently. If the assessment indicates that the learners are struggling to make meaningful learning, the scaffold level increases. If the learners are on the right path, the scaffold gradually fades away (Wood et al. 1976; Belland 2017).

Intersubjectivity refers to a shared understanding between the "scaffolder" (teacher or learning environment) and the "scaffoldee" (learner) regarding a successful performance of a learning task (Belland 2017). It is very important that, when learners work independently at the end of the instruction, they should be able to recognize whether they are doing so correctly or not (Wood et al., 1976; Wertsch and Kazak 2005; Belland 2017). Intersubjectivity is crucial in building the learners' self-efficacy, i.e, "the context-specific belief that one can perform successfully" (Myyry and Joutsenvirta 2015, p.121). The third and fourth columns of Table 1 present these three features of the scaffolding instructional method and the instructional techniques applied to manifest the three features.

Instructional scaffolding is a perfect candidate for "casting" the complex and dynamic problem via the OILE. This is because it:

- comprises most of the key features of the six instructional design models such as task (content) centered design, simple to complex progression of learning tasks with a holistic perspective, provision of the right support when needed, and focus on transfer of knowledge and skills into real world tasks;
- requires the learners to complete the entire learning tasks, which consist of all the knowledge and skills the learners need to gain to become more expert.

4.4 Identify Instructional techniques

4.4.1 Instructional techniques for dynamic assessment

Dynamic assessment is done using multiple-choice questions (MCQ) and open-ended questions (OEQ). The format of the MCQ is consistent throughout the learning environment with four alternatives, except in two specific questions that have only two alternatives. There is only one correct choice per question and learners can only choose one answer at a time. In the OEQ format, learners are asked to predict behavior over time graphs. The students draw their predictions on the OILE and submit their answers.

The learning material is designed in a way that, at each stage of the learning activity, learners are posed a question to solve a problem. The leaners work on the question and give their response either by choosing one of the MCQ alternatives or by drawing behavior graphs. The questions range from identifying a vivid problem to hypothesizing a causal structure responsible for that problem and analyzing the relationship between the suggested structure and the consequent dynamic behavior by building computer models. During the model-building phase, learners are required to work with a modeling software installed on their local computers. In this stage, the learners are often required to switch between the OILE and the modeling software, so that they can have hands on activities.

The questions are arranged in sequences called 'learning paths'. A learning path is a sequence of questions that learners pass through, while working on the complex and dynamic problem on their own pace and time (see Figure 3). Each learner has her/his own unique learning path. In general, there are linear and branching sequence questions in the learning path of a learner. Linear sequence questions are those where a learner moves to the next question after finishing the previous question without any precondition. Branching sequence questions are those where the next question depends on the performance of the learner in the previous question. The branching technique is discussed in detail in the next subsection.

4.4.2 Instructional techniques for provision of just the right support

Five instructional techniques have been used in the OILE to 'provide just the right support': storytelling, repeated trial, feedback, feed-forward and item branching.

The storytelling technique is used to present the content of the learning material. It is used to contextualize the students' learning. This technique helps to link what students already know with the new information. It also helps to provide important information to learners that help them solve the learning tasks. The storytelling technique is used in almost all of the six instructional design models under different names: Adjusting scaffolding (Jonassen, 1999; Reigeluth et al., 2017), Supportive information (Van Merriënboer and Kirschner, 2017), and Activation of prior knowledge (Merrill, 2013; Francom and Gardner, 2014).

The repeated trial technique is used to give students the opportunity to try a question multiple times. The students have three chances to try to answer a MCQ that has four alternatives. This technique helps to design different levels of support for the students. A student who has failed to respond correctly to a question twice receives more support than those who have failed only once.

Repeated wrong choices of students' serve as good indicators for possible misconceptions, which the teachers can address during face-to-face instructions. Also, they help the teachers and the instructional designers to identify learning tasks that need revision to improve the quality of the OILE. From the students' perspective, the repeated wrong answers help them recognize their performance level and their progress in the learning tasks.

The third and fourth instructional techniques are provision of feedback and feed-forward. Gagné (1985) underscores that provision of timely and informative feedback is crucial for learning. In the OILE, every time students respond to a question a feedback page opens. If the question is an OEQ, then the students receive suggested answers so that they can compare their response with the suggested answers.

However, in the case of MCQ, the students receive different feedback based on their individual performance. If the chosen alternative is correct, the students get the reason why that alternative is correct and why the other alternatives are wrong. Such feedback has two objectives: (1) to make sure that the students know the correct reason that their responses are correct, thereby strengthening intersubjectivity between the scaffoldee and the scaffolder; (2) to prevent the impact of "guessing" on subsequent tasks, thereby serving as a feed-forward.

If the students' responses are wrong and are not their third trials, they get either a corrective feedback or an ordinary feedback with item branching.

A corrective feedback is a feedback that explicitly shows the reason why the students' answers are wrong. Whereas an ordinary feedback with item branching is a feedback that simply tells the students their reply is incorrect. Unlike the corrective feedback, the students do not receive information about why their answers are wrong. Rather, the students are asked to branch to tasks that are easier than the previous but under the same conceptual framework so that they can figure out on their own why their previous responses were wrong.

The option for providing either 'corrective feedback' or 'ordinary feedback' with item branching depends on individual students' learning paths and the stages at which they are in the learning tasks.

Students receive corrective feedback while they are in the early stages of problem identifications. Students' continued engagement in the learning environment can be affected by their early perception regarding what they are going to do (Jonassen, 1999). The learning tasks and the support provided during the early stages of the learning process should help the learners understand the problem statements clearly.

Corrective feedbacks gradually fade away and are replaced by ordinary feedbacks with item branching as students advance through the learning material. Students are allowed to branch up to three levels. However, if the students fail to respond correctly at the lowest level, they will get corrective feedback. If the students are successful in responding to the lower level questions, they will move up to higher levels and work again on the questions they failed to respond correctly. In doing so, the students move up and down the ladder. If the students respond correctly to the questions at the top level, they progress to a relatively complex task. As the learners progress through the learning material and gain more expertise, the item branching reduces from three levels to two levels and finally to one.

4.4.3 Instructional technique for intersubjectivity

In the OILE, intersubjectivity is maintained by (1) allowing students to pass through iterative steps at each stage of the learning material and by (2) providing summaries at the end of certain group of learning activities.

Every time students are asked to identify a problem, for example, they will be asked first to identify the variable that represents the symptom of the problem (the stock/ accumulator). Then they will be asked to identify the variables that cause the stock/ accumulator to change (flows) and finally variables that influence the flow rates to change (auxiliary variables or parameters). Van Merriënboer and Kirschner (2017) classify such skills as 'recurrent constitute skills'. These 'recurrent' skills could be acquired either by following certain procedures and/or rules or by "continually practicing them in order to automate those constitute skills" (p.97). However, skills such as identifying a stock or a flow variable from a problem description are achieved by building schema of those variables (Jonassen 2000). Van Merriënboer and Kirschner (2017) classified these skills as 'non-recurrent constitute skills'. The techniques used in the OILE help to strengthen the construction of both 'recurrent' and 'non-recurrent' constitute skills, thereby establishing intersubjectivity between the scaffoldee and the scaffolder.

During the model behavior analysis stage, students are asked to chop time on the basis of monotonic behavior developments, so that they can explain each monotonic development referring back to the structure of the model. In doing so, students practice and strengthen their analytical skills. Van Merriënboer and Kirschner (2017) call this 'part –task practice'. The main objective of the part–task practice is to develop particular sub-skills to acquire automatic performance (p.49).

To reinforce certain subtle concepts of the learning material, summaries are provided at the end of related learning activities. In the summaries, the main insight of each learning task is highlighted so that students can easily integrate the new concepts with the learning objectives.

4.5 Design the interface and implement the tool

The OILE is a web-based instructional tool designed to manifest the instructional method and techniques described in the previous subsections. The OILE is designed around the Mr. Wang case study.

The five tasks of the case study (see section 4.2) are organized under three different OILEs for ease of management. The first OILE consists of Task 1 and Task 2. The second consists of Task 3 and Task 4 and the third OILE consists of Task 5. However, all three OILEs have the same characteristics and they have similar interface design.

Under each OILE, a task is further divided into items. An item is a specific challenge presented to a student. An item comprises stimulus material and a question (see Figure 2). The stimulus material manifests the storytelling technique (section 4.4) and is a description of a problem a student is supposed to solve. Stimulus materials are presented as text, behavior graphs, causal loop diagrams, and/or built-in models. Simulation buttons and time series graphs that display computer simulation results accompany built-in models. The stimulus material gives context for a challenge presented in the form of a question. A question is a specific challenge a student is supposed to solve on the basis of the stimulus material. The case study consists of 105 questions in total.

Two user interface design formats have influenced the interfaces of the OILEs: the user interface design of OECD (2013) and the storyboard format of Alessi and Trollip (2001). The OILE's interface is divided into different pages: a welcome page, task description page, item description page, and supportive information provision page.

Figure 1 shows a screenshot of a sample welcome page. The welcome pages introduce the general objective of the case study. Navigation buttons placed at the top and bottom right of the screen guide the students' movement through different pages. Buttons that lead to the immediate next page (default next page) are highlighted with bright green colors. However, students have the option to go to pages other than the 'default next page' using navigation buttons that are not highlighted. For example, a student who comes from a task description page to the welcome page for the second or third time can jump directly back to the task description page (where the student was) by clicking on the appropriate navigation button (Last Visited Page).

Figure 2 shows a screen shot of a sample item description page. In the item description page, stimulus material appears in the top part of the screen. The question appears in the lower part of the screen, and borders visually separate it from the stimulus. The top left of the screen displays the name of the case study.

The navigation buttons placed at the top right of the screen guide the students' movement through different pages. Item and task numbers are shown at the top left edge of the screen. The multiple-choice alternatives are placed at the bottom left edge of the screen.

The OILE is built on an interface of a computer modeling software, Stella Architect version 1.4. The OILE has been hosted on the isee exchange online platform (https://exchange.iseesystems.com/login). It can run on any web browser. However, students need special permission to access the OILE page.

Once students log into the OILE page, a special tracker built on the Stella Architect software tracks their process log information. The tracker records information such as name, students' performance in the case study, the pages the students have navigated, and the amount of time they have spent on a page. It also records what kind of support the students have received. The process log information was collected in the form of comma separated values (csv) files and time series graphs. Sample time series graphs and csv files are presented in Figure A1 and Table A1 in Appendix A, respectively.

The tasks in the OILE require students to engage in hands on modeling exercises. Hence, students are required to install modeling software such as Stella Architect into their local computers so that they can easily switch between the online material and their modeling software.

5. Sample results and discussion

October 2017 and 2018, first year system dynamics master program students (57) at the University of Bergen, Norway, used the OILE to carry out the Mr. Wang Bicycle Repair Shop case study, a part of the students' mandatory course work.

In its original pencil and paper format, students were introduced to the case study by a professor. The students submitted their work after working for a week. In case they encountered challenges while working on the case study, they consulted the teaching assistants. After submission, the professor reviewed the case together with the students. In its new, blended learning format, the professor introduces concepts relevant to the case study whereupon the students, in the course of the following week, work entirely using the OILE on their own time and at their own pace. After submission, the professor reviews the case together with the students. However, before submission they do not consult with the teaching assistants because that function is served by the OILE.

5.1 Sample assessments on students' cognitive development

All the students completed the learning tasks of the OILE. More than 50% of the students worked through the case study twice, merely on their own initiative. More than 10% of the students worked through the OILE three times or more. This paper presents results only from the students' first time efforts.

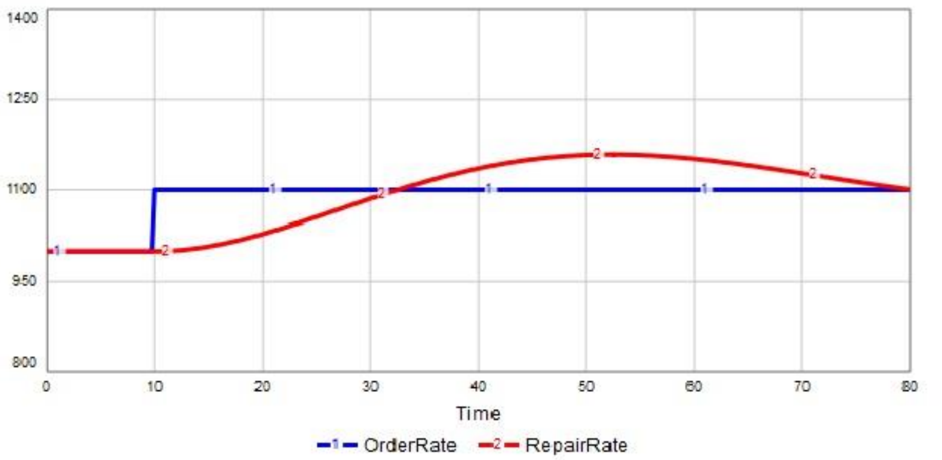
Students' cognitive domains of learning have been assessed based on the process log information. Based on this information, the students' learning paths have been drawn using GraphViz software (http://graphs.grevian.org/graph). Figure 3 portrays one student's learning path while the student was performing a sequence of tasks associated with problem identification and different stages of model building. The green lines represent progress in performance and the red lines represent movement to remedial questions. This student has struggled to perform well in problem identification tasks. Consequently, the student received more support while solving these tasks. Possibly, as a consequence, the student's performance improved to a significantly higher level of performance while addressing the subsequent model building tasks.

To further demonstrate the support offered by the OILE and the resulting progress the students demonstrated, an instance of learning is presented below.

To test the students' understanding of stocks (accumulators) and flows (those that increase/drain the stocks), they were asked to address two cases (Case 1 and Case 2) that require graphical integration. Each case has three questions organized in three levels. The questions under Case 1 focus on concepts associated to the maximum level of a stock and the condition that lead to the maximum level. Whereas questions under Case 2 focus on the minimum level of a stock and the condition that lead to the minimum level.

Two questions, Q2.3 and Q2.4 were at the first level of Case 1 and Case 2, respectively. These questions are similar to the "department store task" (see Sterman 2002; Cronin and Gonzalez, 2007). In the department store task, Sterman (2002) gave students a time series graph that shows the number of people that are entering and leaving a department store over a period of 30 minutes. The students were asked four question. Two of them asked the students to determine *when* the most and least number of people were in the department store. They turned out to be very difficult questions to answer correctly (Sterman 2002). Cronin and Gonzalez (2007) also found the same result in a separate study.

In the cases discussed in this paper, the student were asked the two questions (Q2.3 and Q2.4) based on Figure 4. The figure shows the flow of bicycles in to and out of Mr. Wang's repair shop over the first 80 days. OrderRate refers to the number of bicycles that arrive at Mr. Wang's shop for repair per day and RepairRate refers to the number of bicycles that are repaired and delivered back to customers per day.



Notes: OrderRate: the number of bicycles that arrive at Mr. Wang's shop for repair per day; RepairRate: the number of bicycles that are repaired and delivered back to customers per day.

Figure 4. The flow of bicycles in to and out of the Mr. Wang bicycle repair shop

In the first level of Case 1, the students were asked to determine *when* the number of unrepaired bicycles in the repair shop reaches a maximum during the period in question (see the screenshot of the question in Figure A2 in Appendix A). Students were provided with four alternatives and they had to choose one as their answer. Those students who failed to choose the correct answer were asked to branch to another question under Case 1 (level 2 question). This branched question asked students to determine the condition under which the backlog (physical store of unrepaired bicycles) would be at its highest level (see Figure A3 in Appendix A). The main argument for providing such branched question is that if the students understand the condition under which the backlog would be at its highest level, they will be able to answer the question at level 1 when they redo it. Again, the students had four alternatives to choose from.

Those students who failed to respond correctly in the branched question were asked to branch further to another question, which is the lowest in the hierarchy of Case 1 (level 3). At this third level, the students were presented with a metaphor of a bathtub and were asked to distinguish the conditions under which the bathtub's level would increase, decrease and remain the same (see Figure A4 in Appendix A). Here again the students had four alternatives to choose from.

Those students who responded correctly at this third level received the reasons for why their answer was correct and why the other alternatives were incorrect (see Figure A5 and A6 in Appendix A). Consequently, these students were asked to move up to a higher level and retry the question they originally failed to answer correctly.

Those students who failed to respond correctly at the third level had two more chances to retry the question. Every time they failed to respond correctly, they each received feedback that informed them why their response was incorrect.

Those students who failed to respond correctly in their third attempt received feedback that informed them of the correct answer and explained for each alternative, why that alternative is a correct/incorrect answer (see Figure A7 in Appendix A). Subsequently, the students were asked to move up to a higher level and retry the questions they originally failed to answer.

All the students who had worked on the first question of Case 1, whether they got it right on their first attempt or failed and went down and up the branching questions, moved to the first level of Case 2. Case 2 is an analogous situation of Case 1. But, it challenged the students to determine *when* the number of unrepaired bicycles in the repair shop reaches a minimum in the first level question (Q2.4) and asked them to recognize the condition that lead to the lowest level of the backlog in the subsequent branching question. The figures and the branching techniques used in Case 2 were similar to Case 1. If the students had learned from the questions and the support they received in Case 1, it would be legit to expect them performance better in Case 2. Research, however, shows that working on the questions without having any intermediate support/feedback has not brought any change on the students' performance on the analogous questions (Sterman 2002; Cronin and Gonzalez, 2007; Cronin et al., 2009).

Table 2 summarizes the distribution of the students who responded correctly to the two first level questions of Case 1 and Case 2 and to the subsequent branching questions. In the OILE, a numbering system was used to differentiate the branched questions from the first level question. Hence, Q2.3.1 and Q2.4.1 represent the second level, and Q2.3.1.1 and Q2.4.1.1 the third level of Case 1 and Case 2, respectively.

Table 2. Distributions of correct responses to questions under Case 1 and Case 2

Question hierarchy	Case 1 (Maximum level)	Case 2 (Minimum level)
Level 1	Q2.3 (49% of total)	Q2.4 (68% of total)
Level 2	Q2.3.1 (62%* = 32% of total)	Q2.4.1 (61%* = 19% of total)
Level 3	Q2.3.1.1 (64%** = 12% of total)	Q2.4.1.1 (100%** = 13% of total)

Notes: N= 57. Level 1: Questions that asked students to determine when the highest (Q2.3)/lowest (Q2.4) number of unrepaired bicycles were in the shop. Level 2 & 3: Branching questions that support those students who failed to respond correctly to Level 1 questions. *Indicates % of correct responses from those incorrectly responded at Level 1. **Indicates % of correct responses from those incorrectly responded at Level 2.

Of the 57 students who had used the OILE, only 28 (49%) students determined correctly the time at which the highest number of unrepaired bicycles were in the repair shop. Of the same 57 students, the number of students who subsequently determined correctly the time at which the lowest number of unrepaired bicycles were in the shop was significantly larger (39 [68%]) compared those who correctly responded at the first level of Case 1.

The table also shows that of those who failed to respond correctly at the first level (51% in Case 1 and 32% in Case 2), fewer students failed to answer the branching questions compared to the higher percentage of students who failed at the first level. This is true for both Cases.

The result observed in the first question of Case 1 (Q2.3) is similar to the findings of other studies such as Sterman (2002) and Cronin and Gonzalez (2007). However, the 19% increase in the students' performance, from 49% in the first question of Case 1(Q2.3) to 68% in the first question of Case 2 (Q2.4), and the relatively better performance observed in the branching questions of both cases were not seen in other studies. This paper argues that such an increase in performance may be attributed to the support (scaffold) that students received using the OILE, i.e, the adequacy of the various levels of support provided by the OILE.

5.2 Assessment on students' affective domains

Two questionnaires (survey research method, Fowler, 2014) based on prior research (Taylor-Powell and Renner, 2009; Maor and Fraser, 2005; Berkeley Center for Teaching & Learning, n.d) were distributed among the students to assess the affective aspects of learning. The questionnaires were designed to answer the third research question of the paper - Can personalized and adaptive OILE support students' affective domains of learning in their study of CDS?

The first questionnaire was administered as soon as the students had completed Tasks 1 and 2 of the learning material, whereas the second was administered after they had completed Tasks 3, 4 and 5. Fifty-three students out of fifty-seven (93%) responded to the two questionnaires. A total of 38 questions were administered through the two questionnaires. These 38 questions are summarized in six major categories as shown Table 3. A detailed account of the students' response to questionnaire 1 and 2 is provided in Appendix A (see Table A2).

Table 3. Students' response to Questionnaire 1 and 2

S.No	Questions	Strongly Disagree (%)	Disagree (%)	Neither Agree or Disagree (%)	Agree (%)	Strongly Agree (%)
1	Experience with the user interface of the OILE: It has clear interface It is easy to navigate through the OILE The OILE does not have unnecessary long texts that hinder my learning	1	11	13	57	18
2	Attitude towards the content of the learning and its organization: It is appropriate to students of my level I have learned from the tasks It helped me learn step by step	1	5	17	54	23
3	Attitude towards the feedback offered: I have read all the feedback I have learned from the feedback	3	18	15	53	11
4	Attitude towards application of the knowledge and skills they acquired in a previous course: The OILE gave me the opportunity to practice the skills I gained during a previous course	1	6	13	68	12
5	Belief about their learning: I have understood the objective of the case study I have understood the main problem in the case study I have gotten deeper insight about the main concepts of the case I am ready to embark on the next challenge of the course	1	4	18	55	22
6	Regarding future use of the OILE: I recommend other system dynamics students of my level to make use the OILE	1	0	15	46	38

Notes: N = 57, response rate 53/57 = 93%

The results are as follows:

- More than 75% of the students believe that the OILE has a clear user interface and that it is easy to navigate. They also indicate that the texts used in the OILE are not too long to hinder their learning.
- More than 77% of the students believe that the content is appropriate to their level and they felt they had acquired knowledge in a step-by-step manner.
- More than 64% of the students believe that they had read and learned from the feedback offered.
- More than 77% of the students claimed that they had understood well the learning material and felt they were ready to move to the next challenge of the course.
- More than 84% of the students recommended that other system dynamics students, who are at the same level as them, make use of the OILE.

A Wilcoxon Signed-Ranks test was conducted to evaluate whether students showed greater satisfaction in questionnaire 2 compared to questionnaire 1 (see Table 4). The results indicated statistically significant differences for question 3 (attitude towards the feedback offered), $Z = -2.71$, $p = .007$ and for question 5 (belief about their learning), $Z= -2.00$, $p = .046$. The means of the ranks in favor of the OILE in questionnaire 2 were Mdn = 6.00 (for question 3) and Mdn = 2.50 (for question 5), while the means of the ranks in favor of the OILE in questionnaire 1 were Mdn = 6.00 (for question 3) and Mdn = .00 (for question 5). For the other four questions, the Wilcoxon Signed-Ranks test indicated that there were no statistically significant differences in the satisfaction level of the students between the two questionnaires.

Table 4. Results of the Wilcoxon signed-Ranks test

		N	Mean Rank	Sum of Ranks	Z	Asymp. Sig. (2-tailed)
Q2q1 – Q1q1 (Experience with the user interface of the OILE)	Negative Ranks	2[a]	2.50	5.00	.000[d]	1.000
	Positive Ranks	2[b]	2.50	5.00		
	Ties	49[c]				
Q2q2 - Q1q2 (Attitude towards the learning task)	Negative Ranks	1[a]	3.50	3.50	-1.633[e]	.102
	Positive Ranks	5[b]	3.50	17.50		
	Ties	47[c]				
Q2q3 - Q1q3 (Attitude towards the feedback offered)	Negative Ranks	1[a]	6.00	6.00	-2.714[e]	.007*
	Positive Ranks	10[b]	6.00	60.00		
	Ties	42[c]				
Q2q4 - Q1q4 (Attitude towards application of their previous knowledge)	Negative Ranks	3[a]	2.50	7.50	-1.000[f]	.317
	Positive Ranks	1[b]	2.50	2.50		
	Ties	49[c]				
Q2q5 - Q1q5 (Belief about their learning)	Negative Ranks	0[a]	.00	.00	-2.000[e]	.046*
	Positive Ranks	4[b]	2.50	10.00		
	Ties	49[c]				
Q2q6 - Q1q6 (Regarding future use of the OILE)	Negative Ranks	1[a]	5.00	5.00	-.707[e]	.480
	Positive Ranks	4[b]	2.50	10,00		
	Ties	48[c]				

Notes: Total N = 53. Q1 – Questionnaire 1, Q2 – Questionnaire 2, qi – question number.
[a]Response in Q2 < Response in Q1; [b]Response in Q2 > Response in Q1; [c]Response in Q2 = Response in Q1; [d]The sum of negative ranks equals positive ranks; [e]Based on negative ranks; [f]Based on positive ranks; *p values below α = 0.05.

Here, it is important to highlight that students had developed a more favorable attitude towards the importance of the feedback they received through the OILE and their attitude had grown more favorably as they progressed through the learning materials. Similarly, their beliefs about their learning became stronger as they progressed through the learning materials. Furthermore, from the analysis of the Wilcoxon test, it can be inferred that the students did not find significant differences across the interfaces of the various OILEs; this signifies the consistency in the design of the OILE.

Based on the overall analyses of the two questionnaires, the paper concludes that students have had a positive experience and developed a friendly attitude towards the OILE.

5.3 Intervention strategies and limitation of the study

5.3.1 Intervention strategies

During the design of the OILE, three intervention strategies (immediate, intermediate and long term) were designed to tackle challenges students might face while using the OILE.

The immediate intervention is one that is offered through the OILE and it is provided when students struggle to perform well. It is offered in the form of support as described in section 4.4.2.

The intermediate intervention is one that follows preliminary assessment of the learning analytics. One of the most notable intermediate interventions made was the introduction of a new case study following the preliminary analysis of the OILE's first time use (during the year 2017). The new case study has a concept similar to the one used to design the Mr. Wang OILE. It has been designed to reinforce the concepts addressed with the support of the OILE and also to access the transferability of the knowledge and skills gained while using the OILE. It has been designed using a paper and pencil format and was administered to the 2018 system dynamics master program cohort immediately after they had been exposed to the Mr. Wang OILE. Currently, the findings from this new case study and from the OILE experiment are undergoing detailed analyses to be published at a later stage.

The long term intervention is one that aims at improving the quality of the OILE based on feedback from the questionnaires and analyses of the learning analytics. Results from this intervention will also be communicated in future publications.

5.3.2 Limitation of the study

This paper is delimited to the provision of support to individual students during their study in and about CDS. However, future studies need to document how to foster collaborative learning in and about CDS while accounting for individual students need. Most of the existing platforms that support collaborative learning in and about CDS focus on the dynamics of the groups' interaction without offering detailed account to the individual students need.

Another major limitation of the study is its inability to generate reports automatically that are easy to read and to interpret. Currently, the students' data was collected first in the form of CSV files and then manually converted into spreadsheets before the data was coded into learning paths with the help of the GraphViz software (http://graphs.grevian.org/graph). With current advancement in artificial intelligence, the automatic generation of such reports should be possible soon.

A third limitation of the study that is worth of mentioning here is the diversity of the educational media used in the OILE. The study is limited to the use of texts, graphs, and simulations. However, in future, the choice of educational media need to be broadened, particular, the inclusion of audios and videos should be considered. The inclusion of such medias could potential increase the learners' active engagement with the OILE.

With regard to students' assessment, the current study relied heavily on the use of multiple-choice questions and on open-ended questions that ask students to estimate the over time development of variables that have significant impact on the Mr. Wang's problem formulation. However, future work should consider diverse assessment techniques, such as questions that address the students' comprehension, reflective questions and essays that encourage students to describe and respond to the learning tasks using their own words.

Despite the limitations mentioned above, the study showed stronger evidence in the students' cognitive as well as affective domains of learning. This is evidence of the effectiveness of the proposed design framework aimed at facilitating students' learning in and about complex, dynamics systems. There is a strong belief that, if properly applied, this five-step design framework for personalized and adaptive learning, together with the three key features of the OILE, would play a significant role in the students' learning in and about CDS.

6. Conclusion

Research shows the world is facing a wide range of increasingly complex, dynamic problems in both the public and private sectors; climate change, unemployment, health problems, famine, migration, supply-chain problems etc. create challenges for private and public organizations (OECD, 2017). The problems we face often have a dynamic nature and originate from systems that cause the problem behavior to develop over time. This dynamic development originates from the internal structure of the system (Diehl and Sterman, 1995; Davidsen, 1996). Research demonstrates that we are not well prepared to meet the challenges presented to us in the form of dynamic complexity, neither mentally nor in the form of theories, methods, techniques, and tools (Davidsen, 1996; Spector and Anderson, 2000; Jonassen, 2000; Ifenthaler and Eseryel, 2013; Van Merriënboer and Kirschner, 2017).

The objective of this project is to support learning in and about complex, dynamic systems by developing effective instructional methods, techniques and tools; so that students can develop deep intuitions about complex, dynamic systems and an ability to reveal quick fixes that ignore real world complexity (OECD, 2017; Sterman, 2011). For this purpose, the creation of a personalized and adaptive OILE is proposed.

This paper demonstrates how the OILE supports individual learners in their study of CDS. The OILE has been developed based on six models of instructional design that follow a holistic instructional design principle; 4C/ID, First Principles of Instruction, CLE, TCI, Cognitive Apprenticeship, and Elaboration Theory. The OILE has the following three characteristics:

A. It presents an authentic, complex dynamic problem that the learner should address in its entirety. It then proceeds to allow learners to progress through a sequence of learning tasks from easy to complex.

B. When solving the problem, learners interact with the OILE. After completion of each learning task, the OILE provides learners with supportive information based on their individual performance. The support fades away as learners gain expertise.

C. It tracks and collects information on students' progress and generates learning analytics, which are used to assess students' learning.

The progress log information was used to assess the cognitive domains of students´ learning, whereas the affective domains of students' learning were assessed using two questionnaires. Sample results from the progress log of a student demonstrates that the OILE has facilitated the students' cognitive development. Analyses of the questionnaires show that students firmly believe they have been through an effective learning experience while working within the OILE.

The literature makes the case for the importance of and difficulty in comprehending CDS. In the study, supportive evidence from the students´ progress in the cognitive domain, as well as their confirmative response in the affective domain, allow the paper to conclude that the use of personalized and adaptive OILE to support learning in and about complex, dynamic systems is promising.

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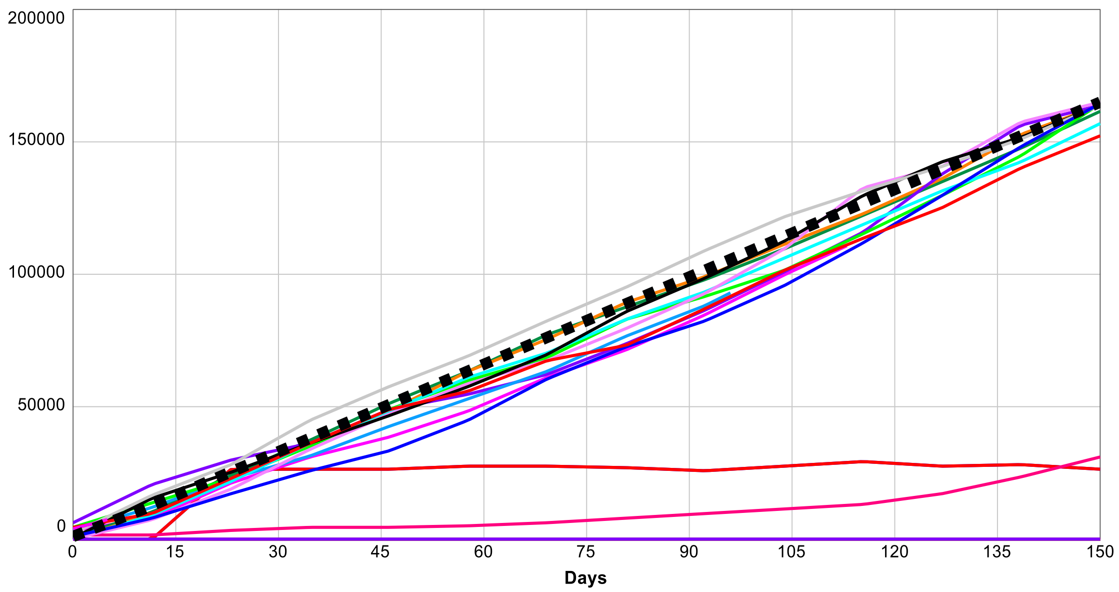
Appendix A

A.1 Sample time series graph

Figures A1 shows sample time series graph drawn by students. The students were asked to estimate the development of a Backlog (an accumulator) over 150 time units. Initially, the Backlog had 1000 units and one inflow that initially set to 1000 units per day. At time 10, the flow rate stepped up by 100 units and remained there for the duration of the simulation:

Inflow = 1000 + STEP (100, 10)



Notes: Initial Backlog = 1000 units, Inflow = 1000 + STEP (100, 10); the black dotted line is the actual development of the backlog; the thin colored lines are students' estimations

Figure A1. Sample time series graph: Students' estimate for the development of a backlog over a period of 150 days

Each line in the time series graph represents one student's response. To keep the students' anonymity, personal information was deleted from the time series graph.

A.2 Sample csv files

Table A1 shows sample comma separated values (csv) files that have been converted into spreadsheet data. The spreadsheet displays three students learning analytics. To keep the students' anonymity, personal information was deleted from the spreadsheet. The spreadsheet shows the first 31 data points for each student, which include the different pages the students had visited, the time the students had arrived on a specific page and the amount of time the students had spent on the page. During the analysis, the pages have been coded as either welcome page, task description page, item description page or feedback page. These coded pages served as a base for drawing the students' learning paths.

Table A1. Sample csv file of three students converted into spreadsheet data

Student A			Student B			Student C		
Page number	Arrival time	Time spent (Seconds)	Page number	Arrival time	Time spent (Seconds)	Page number	Arrival time	Time spent (Seconds)
1	October 9, 2017 12:51:03+00	190.875	1	October 9, 2017 12:50:42+00	171.754	1	October 9, 2017 12:54:30+00	35.093
2	October 9, 2017 12:54:13+00	7.014	2	October 9, 2017 12:53:33+00	121.201	2	October 9, 2017 12:55:05+00	53.006
3	October 9, 2017 12:54:20+00	43.904	3	October 9, 2017 12:55:34+00	118.484	3	October 9, 2017 12:55:58+00	115.277
4	October 9, 2017 12:55:04+00	20.373	4	October 9, 2017 12:57:33+00	51.14	4	October 9, 2017 12:57:54+00	16.562
5	October 9, 2017 12:55:25+00	7.261	5	October 9, 2017 12:58:24+00	2.416	5	October 9, 2017 12:58:10+00	44.75
6	October 9, 2017 12:55:32+00	42.141	4	October 9, 2017 12:58:27+00	4.96	6	October 9, 2017 12:58:55+00	79.396
5	October 9, 2017 12:56:14+00	1.353	5	October 9, 2017 12:58:32+00	8.07	7	October 9, 2017 13:00:14+00	217.285
4	October 9, 2017 12:56:15+00	1.09	4	October 9, 2017 12:58:40+00	5.034	8	October 9, 2017 13:03:52+00	39.608
3	October 9, 2017 12:56:17+00	1.241	5	October 9, 2017 12:58:45+00	10.953	9	October 9, 2017 13:04:31+00	609.579
2	October 9, 2017 12:56:18+00	1.113	6	October 9, 2017 12:58:56+00	324.206	10	October 9, 2017 13:14:41+00	11.879
1	October 9, 2017 12:56:19+00	8.579	7	October 9, 2017 13:04:20+00	110.082	22	October 9, 2017 13:14:53+00	37.237
2	October 9, 2017 12:56:27+00	2.044	8	October 9, 2017 13:06:10+00	22.231	23	October 9, 2017 13:15:30+00	4.025
3	October 9, 2017 12:56:30+00	119.18	9	October 9, 2017 13:06:32+00	77.99	35	October 9, 2017 13:15:34+00	181.749
4	October 9, 2017 12:58:29+00	19.549	10	October 9, 2017 13:07:50+00	99.919	36	October 9, 2017 13:18:36+00	16.885
5	October 9, 2017 12:58:48+00	6.846	22	October 9, 2017 13:09:30+00	66.718	48	October 9, 2017 13:18:53+00	139.945
6	October 9, 2017 12:58:55+00	64.003	23	October 9, 2017 13:10:37+00	80.849	51	October 9, 2017 13:21:12+00	3.304
7	October 9, 2017 12:59:59+00	33.669	35	October 9, 2017 13:11:58+00	60.323	53	October 9, 2017 13:21:16+00	10.238
8	October 9, 2017 13:00:33+00	20.44	36	October 9, 2017 13:12:58+00	39.526	54	October 9, 2017 13:21:26+00	39.214

(continued)

Student A			Student B			Student C		
Page number	Arrival time	Time spent (Seconds)	Page number	Arrival time	Time spent (Seconds)	Page number	Arrival time	Time spent (Seconds)
9	October 9, 2017 13:00:53+00	172.477	48	October 9, 2017 13:13:37+00	97.889	61	October 9, 2017 13:22:05+00	118.888
10	October 9, 2017 13:03:46+00	24.513	51	October 9, 2017 13:15:15+00	4.678	62	October 9, 2017 13:24:04+00	3.331
22	October 9, 2017 13:04:10+00	125.509	53	October 9, 2017 13:15:20+00	3.448	74	October 9, 2017 13:24:07+00	14.358
26	October 9, 2017 13:06:16+00	3.77	54	October 9, 2017 13:15:23+00	16.659	75	October 9, 2017 13:24:22+00	62.341
27	October 9, 2017 13:06:19+00	3.419	61	October 9, 2017 13:15:40+00	37.56	76	October 9, 2017 13:25:24+00	86.649
30	October 9, 2017 13:06:23+00	1.647	62	October 9, 2017 13:16:18+00	2.947	77	October 9, 2017 13:26:51+00	59.215
32	October 9, 2017 13:06:25+00	4.735	74	October 9, 2017 13:16:21+00	15.282	78	October 9, 2017 13:27:50+00	129.099
33	October 9, 2017 13:06:29+00	16.884	75	October 9, 2017 13:16:36+00	65.032	79	October 9, 2017 13:29:59+00	32.534
35	October 9, 2017 13:06:46+00	29.947	74	October 9, 2017 13:17:41+00	2.899	80	October 9, 2017 13:30:32+00	5.975
36	October 9, 2017 13:07:16+00	2.022	75	October 9, 2017 13:17:44+00	19.42	114	October 9, 2017 13:30:38+00	16.991
48	October 9, 2017 13:07:18+00	74.982	76	October 9, 2017 13:18:03+00	96.881	115	October 9, 2017 13:30:55+00	3.85
50	October 9, 2017 13:08:33+00	1.714	77	October 9, 2017 13:19:40+00	192.198	149	October 9, 2017 13:30:58+00	29.314
53	October 9, 2017 13:08:35+00	1.637	78	October 9, 2017 13:22:52+00	87.226	150	October 9, 2017 13:31:28+00	33.831

Notes: Personal information such as student name and email address that help to identify individual students are removed from the sample csv file

A.3 Detailed questionnaire data

Table A2. Detailed students' response to Questionnaire 1 and 2

S.No	Questions	Questionnaire	Strongly Disagree (%)	Disagree (%)	Neither Agree or Disagree (%)	Agree (%)	Strongly Agree (%)
1	Experience with the user interface of the OILE: It has clear interface It is easy to navigate through the OILE The OILE does not have unnecessary long texts that hinder my learning	Q1	2	11	11	57	19
		Q2	0	11	15	57	17
		Average	1	11	13	57	18
2	Attitude towards the content of the learning and its organization: It is appropriate to students of my level I have learned from the tasks It helped me learn step by step	Q1	2	6	17	51	24
		Q2	0	4	17	56	23
		Average	1	5	17	54	23
3	Attitude towards the feedback offered: I have read all the feedback I have learned from the feedback	Q1	2	25	13	49	11
		Q2	4	11	17	57	11
		Average	3	18	15	53	11
4	Attitude towards application of the knowledge and skills they acquired in a previous course: The OILE gave me the opportunity to practice the skills I gained during a previous course	Q1	0	6	13	70	11
		Q2	2	6	13	66	13
		Average	1	6	13	68	12
5	Belief about their learning: I have understood the objective of the case study I have understood the main problem in the case study I have gotten deeper insight about the main concepts of the case I am ready to embark on the next challenge of the course	Q1	2	4	19	53	22
		Q2	0	4	17	57	22
		Average	1	4	18	55	22
6	Regarding future use of the OILE: I recommend other system dynamics students of my level to make use the OILE	Q1	0	0	19	45	36
		Q2	2	0	11	47	40
		Average	1	0	15	46	38

Notes: N = 57, response rate 53/57 = 93%. Q1 – Questionnaire 1, Q2 – Questionnaire 2, Average – average of Q1 & Q2

A.4 Sample learning instances

Sample questions that tested the students understanding of stocks (accumulators) and flows (those that increase/drain the stocks).

Figure A2 a screenshot of question Q2.3 that asked students to determine *when* the number of unrepaired bicycles in the Mr. Wang repair shop reaches a maximum during the first 80 days.

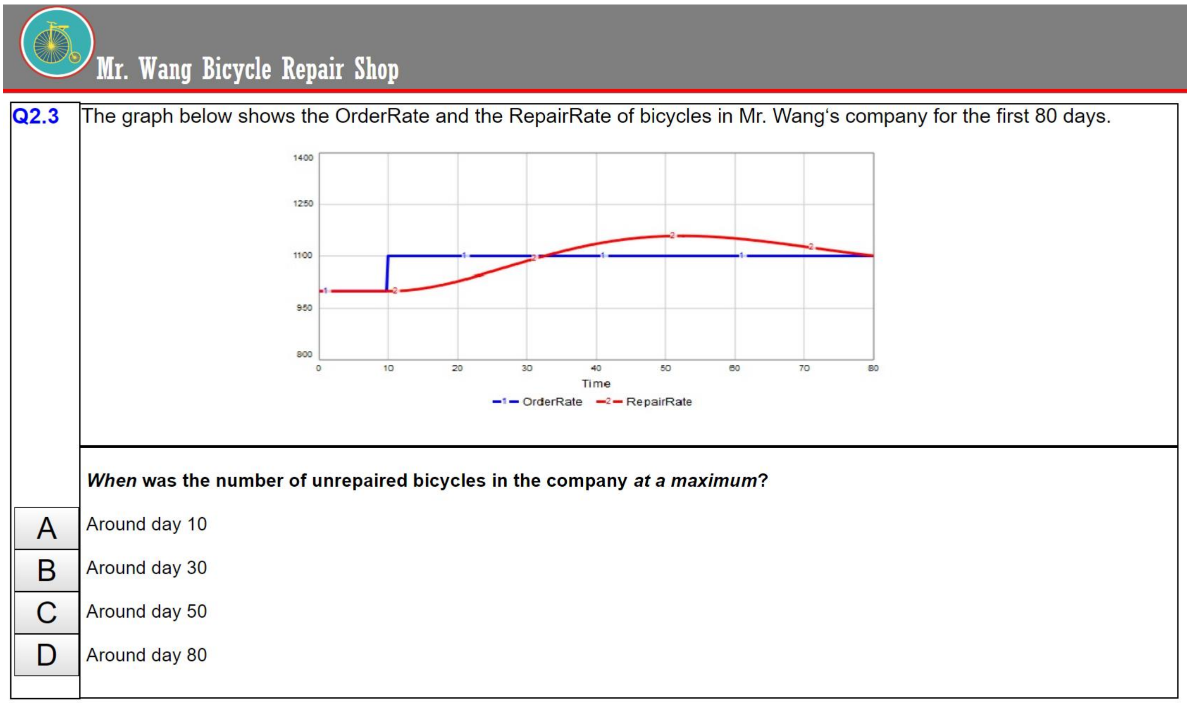


Figure A2. Screenshot of the first level question of Case 1 (Q2.3)

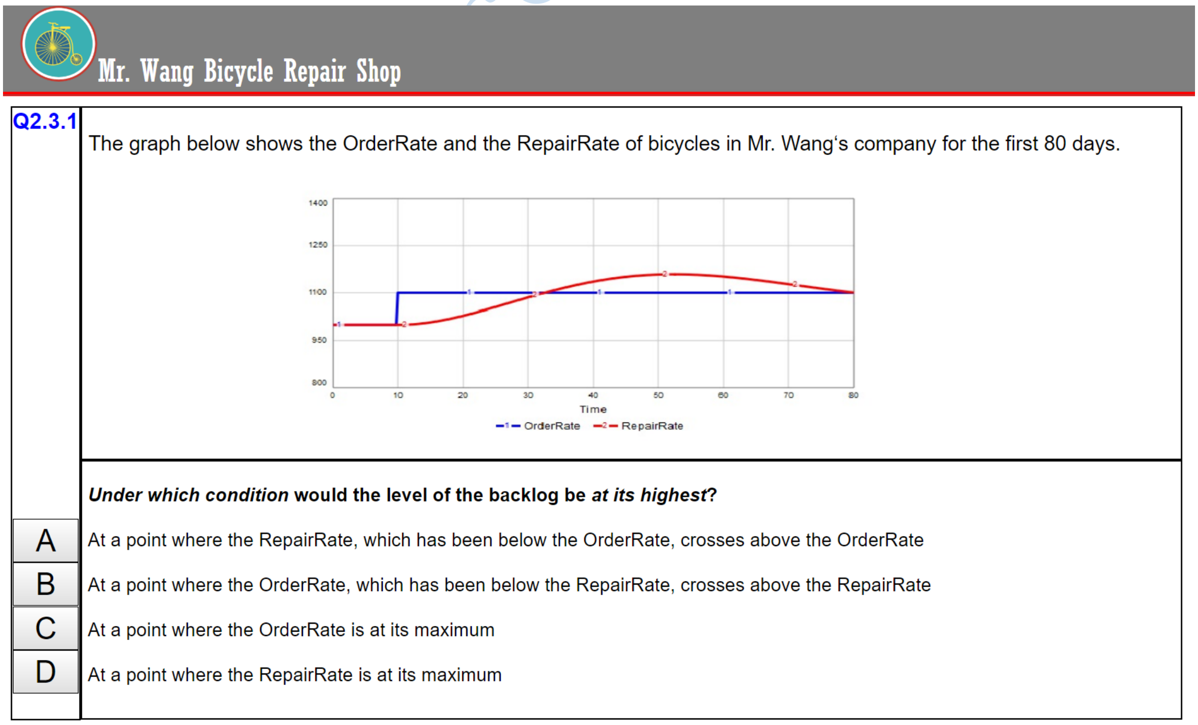


Figure A3. Screenshot of a branching question under Case 1 (level 2)

Those students who failed to respond question Q2.3 in a correct way were asked to branch to question Q2.3.1 (Figure A3).

Those students who failed to respond correctly to question Q2.3.1 were asked to further branch to question Q2.3.1.1 (Figure A4).

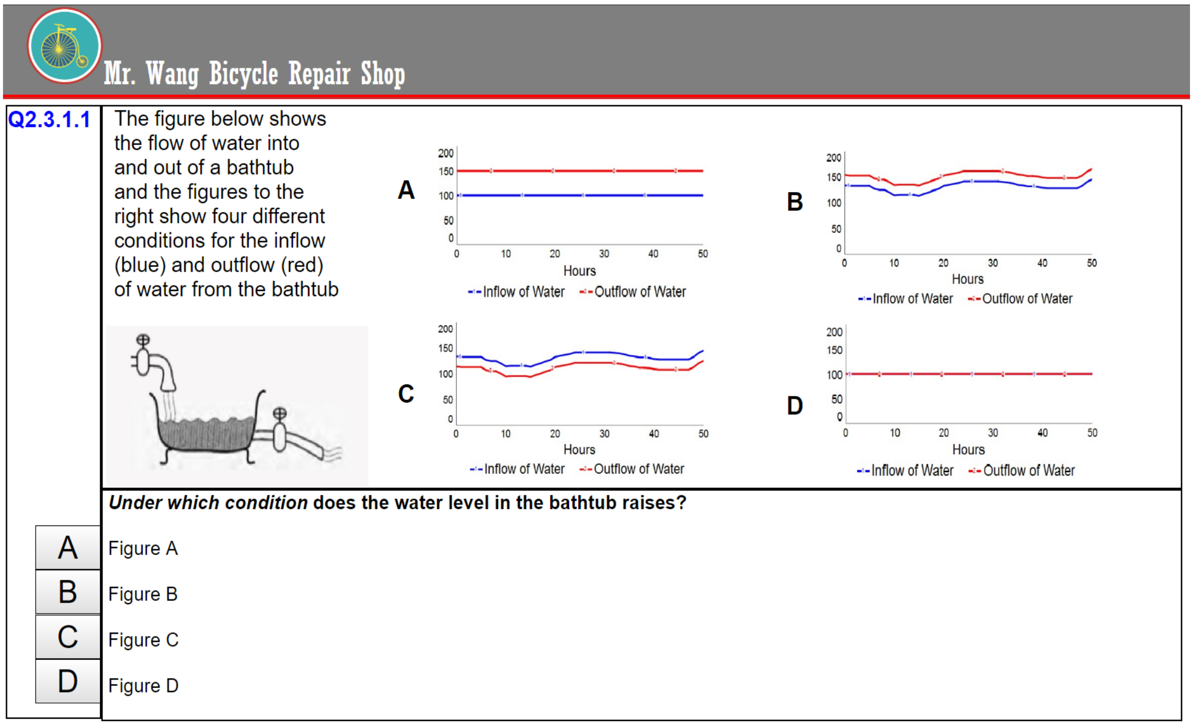


Figure A4. Screenshot of a branching question under Case 1 (level 3)

Students who responded correctly to question Q2.3 were offered a feedback (Figure A5) that informed them the reason why their answer was correct and why the other alternatives were incorrect.

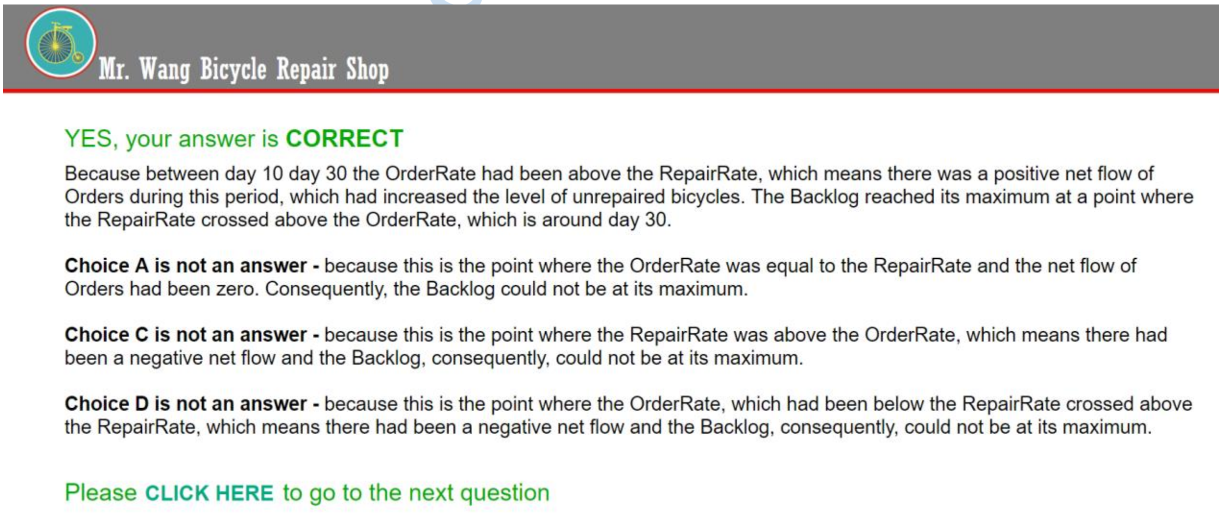
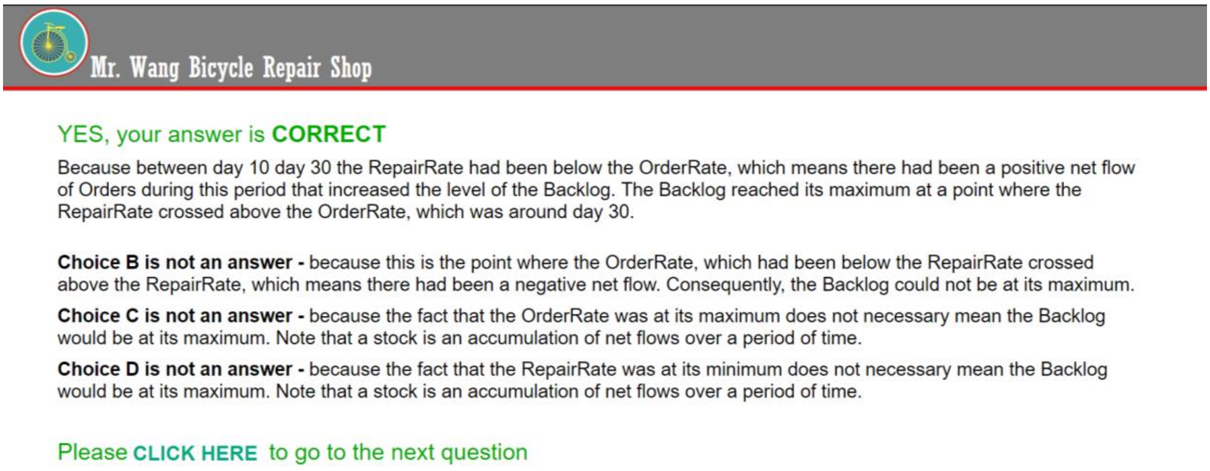


Figure A5. Screenshot of a feedback offered to those who correctly answered Q2.3

Those students who responded correctly to question Q2.3.1 were offered a feedback (Figure A6) that informed them the reason why their answer was correct and why the other alternatives were wrong.



Mr. Wang Bicycle Repair Shop

YES, your answer is **CORRECT**

Because between day 10 day 30 the RepairRate had been below the OrderRate, which means there had been a positive net flow of Orders during this period that increased the level of the Backlog. The Backlog reached its maximum at a point where the RepairRate crossed above the OrderRate, which was around day 30.

Choice B is not an answer - because this is the point where the OrderRate, which had been below the RepairRate crossed above the RepairRate, which means there had been a negative net flow. Consequently, the Backlog could not be at its maximum.

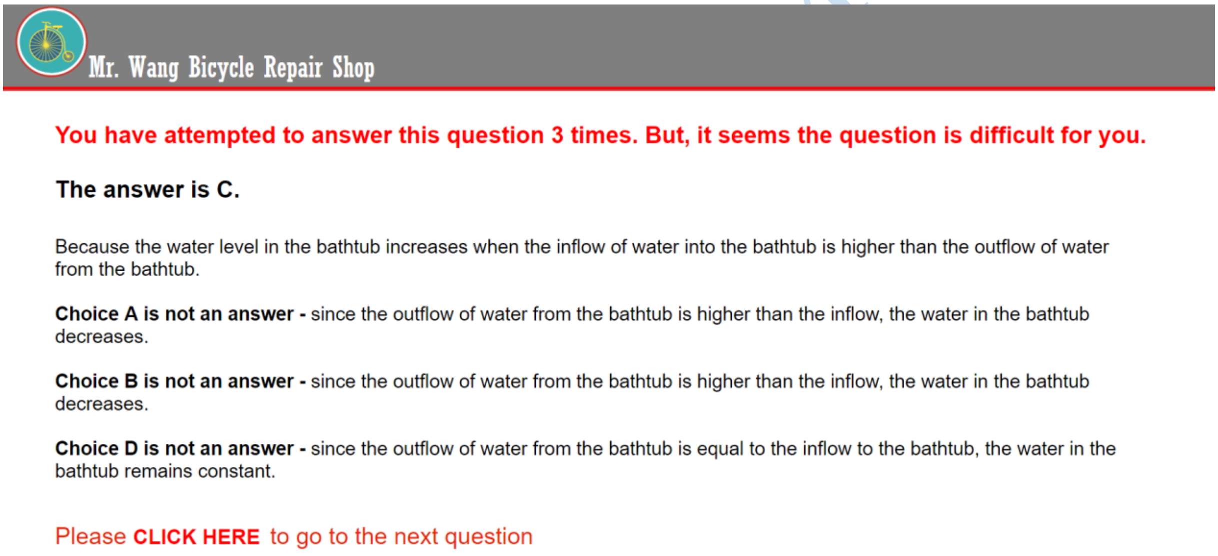
Choice C is not an answer - because the fact that the OrderRate was at its maximum does not necessary mean the Backlog would be at its maximum. Note that a stock is an accumulation of net flows over a period of time.

Choice D is not an answer - because the fact that the RepairRate was at its minimum does not necessary mean the Backlog would be at its maximum. Note that a stock is an accumulation of net flows over a period of time.

Please **CLICK HERE** to go to the next question

Figure A6. Screenshot a feedback offered to those who correctly answered question Q2.3.1

Those students who attempted question Q2.3.1.1 three times and failed to responded to correctly were offered a feedback (Figure A7) that informed them of the correct answer and explained for each alternative, why that alternative is a correct/incorrect answer



Mr. Wang Bicycle Repair Shop

You have attempted to answer this question 3 times. But, it seems the question is difficult for you.

The answer is C.

Because the water level in the bathtub increases when the inflow of water into the bathtub is higher than the outflow of water from the bathtub.

Choice A is not an answer - since the outflow of water from the bathtub is higher than the inflow, the water in the bathtub decreases.

Choice B is not an answer - since the outflow of water from the bathtub is higher than the inflow, the water in the bathtub decreases.

Choice D is not an answer - since the outflow of water from the bathtub is equal to the inflow to the bathtub, the water in the bathtub remains constant.

Please **CLICK HERE** to go to the next question

Figure A7. Screenshot of a feedback offered to those who attempted Q2.3.1.1 three times and failed

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