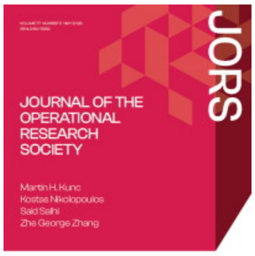

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An international educational framework for teaching simulation

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ABSTRACT
Teaching Discrete-Event Simulation and Agent-Based Simulation is a complex mission faced by academics around the globe. Challenges include a heterogeneous student cohort with varying prior knowledge and skills, diverse emphases across universities and fields of study, and a lack of structured pedagogical guidance in the scientific literature. This paper presents a novel simulation education framework grounded in constructive alignment. It comprises clearly defined learning objectives based on the revised Bloom's taxonomy, an innovative pedagogical structure, and an effective learner-centred assessment portfolio. This approach integrates course design elements and practical application examples for individual and collective learning successes. The framework supports the design of learning environments that foster sustained motivation and positive affective engagement in the learning experience. Drawing on decades of teaching simulation experience in the USA, the UK, and Austria, we provide a structured format and practical guidance for educators to support teaching simulation internationally. We address developments of generative Artificial Intelligence and provide guidance for responsible AI-supported learning. Our generic Customise-Build-Align (C-B-A) framework can be adopted and applied across different simulation courses and curricula. We discuss implications for educators, learners, the simulation community, as well as the framework's relevance for advancing simulation research and practice.

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Education; discrete-event simulation; agent-based simulation; constructive alignment; learning objectives

1. Introduction

The question of how to teach simulation in different educational settings is a perennial one, as evidenced by journal articles (Hoad & Kunc, 2018; Robinson & Davies, 2010) as well as Winter Simulation Conference papers and simulation education track panels discussing the topic over decades (Altiok et al., 2001; Jacobson et al., 1994; Skoogh et al., 2012; Stahl et al., 2003; Van der Zee et al., 2010, 2018). The need to prioritise education as a means for preparing the next generation of simulation modellers has been highlighted by Taylor and Robinson (2006). Collins et al. (2023b) argue that good simulation education contributes to improving the accessibility of simulation. Advancements in computing and more powerful simulation software tools enable researchers and practitioners to model highly complex systems and integrate large amounts of data with greater accuracy and efficiency (Collins et al., 2023a). Advances in Machine Learning and its integration with simulation create new opportunities for scientists, businesses, and government organisations to apply simulation across a wide range of domains such as logistics, manufacturing, and healthcare (Kogler & Maxera, 2026).

As educators, we are responsible for equipping students with the skills and knowledge they need to thrive in an ever-evolving work environment. By including simulation in university curricula, we provide students with hands-on experience in advanced modelling tools that underpin many modern technologies, such as Artificial Intelligence (AI). Simulation is an advanced research method and a foundation for developing, for example, Digital Twins, which are virtual replicas of physical systems for real-time monitoring and optimisation (Franca et al., 2024). From our experience in teaching simulation courses, our students benefit from being introduced to simulation at university and from learning a topical research method (e.g., Digital Twin development, training data, or testbed for Machine Learning). Exposing students to these tools in their academic journey enhances their analytical and problem-solving skills. It significantly improves their competitiveness in the job market, where expertise in simulation and data-driven decision-making is increasingly in demand.

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The focus of this paper is on teaching Discrete-Event Simulation (DES) and Agent-Based Simulation (ABS), rather than teaching *with* simulation. However, the latter can be an excellent appetiser for motivating learners to develop and understand simulation (Olson et al., 2006; Padilla et al., 2016). There are multiple benefits from including simulation courses in university curricula:

- **Understanding systems at a higher level**: A system is more than the sum of its parts, and the relationships between interconnected elements can matter more than the parts themselves. Understanding that everything is a system and decoding the underlying dynamics within a system enable more effective problem-solving.
- **Dealing with variability**: Simulations require students to grapple with variability in ways they typically do not have to. In deterministic modelling, there is no variability. In statistical modelling, variability is considered part of the noise that must be accounted for, not a defining feature of the system that may need to be explicitly worked with.
- **Training critical thinking, creativity, and logic skills**: Students' critical thinking and logic skills are given a good workout in simulation. This is especially the case when building models for complex systems that change over time. Students' creativity is enhanced when looking for ways to simplify or translate the real-world system into a simulation model.
- **Experience in dealing with ill-defined problems**: Simulation problems are often ill-defined and subject to wide interpretation. Unfortunately, students are used to having clearly defined questions with unambiguous solutions. Simulation courses can help students practice identifying, stating, justifying, and communicating clear objectives and possible solutions for scenarios.
- **Attention to detail**: For some students, their simulation course may be the first time they use software or coding to create a model. This forces them to slow down and pay attention to detail, a skill that can benefit them in the future.

There are also challenges associated with teaching simulation courses:

- **Different types of students**: As an instructor, one may teach a wide variety of students (Robinson & Davies, 2010). In this paper, we provide examples for simulation education of engineering, computer science, life sciences, and business students, all of whom could be at the undergraduate, master's, or PhD levels. While this is no different from any other area of Operational Research, the lack of an established standard on how to teach such a course, combined with the potentially challenging nature of the material, can create difficulties for instructors, especially if their backgrounds differ from those of their students.
- **Single simulation course**: Most university departments have a relatively small number of faculty and students working in simulation compared to other areas. As a result, there are few opportunities to introduce students to simulation, often only a single simulation course or even part of an Operational Research course. This can lead faculty to try to include as much material as possible in this single opportunity.
- **Choosing the abstraction level**: Few simulation models are black and white, which means many decisions must be made at every point about what to include in the model and how to approach the modelling more broadly. Balancing simplicity and fidelity can be challenging because of the risk of overfitting and loss of generality, data availability constraints, and computational trade-offs.
- **Challenging verification and validation**: Verification (i.e., ensuring that the model is implemented correctly) can be difficult, due to the complexity of the model logic, software limitations, lack of formal specifications, dynamic and emergent behaviour, and stochastic nature. It may be impossible to guarantee anything beyond "no known errors" (Robinson, 2014; Sargent, 2013, 2015). Similarly, validation (i.e., ensuring that the model accurately represents the real-world system) can be challenging, due to limited availability or quality of historical data, subjectivity, modeller bias, and complex calibration and parameter tuning.
- **Establishing credibility**: Simulation should be easy to understand for stakeholders, which means that many parties may have an opinion on how the model should look to be considered credible. Transparency, documentation, and stakeholder engagement are essential and challenging during the development process (Kotiadis & Tako, 2018; Tako & Kotiadis, 2015; 2018).

The existing literature on simulation education largely consists of context-specific reports on how simulation is taught, while studies on teaching with simulation focus primarily on simulation-based learning, gamification, and serious games. Although this work provides valuable insights into learner engagement and the effectiveness of simulation-supported instruction, it offers little guidance for designing simulation courses, particularly with respect to the systematic alignment of learning outcomes, activities, and assessments. A coherent and adaptable pedagogical framework for teaching simulation across different higher-education contexts remains elusive, underscoring the need for research that develops such structured guidance. This article provides guidance to save new simulation instructors from being left trying to cobble together a course that is suitable for their students. As educators, we recognise that overwhelming students with material is not the best strategy for designing an engaging course from which students will take away a new skill set. We present a framework that simulation educators can use to design their own simulation courses to best suit their and their students' needs to provide answers regarding: What should be taught in a simulation course? How can an effective, motivating, and high-quality simulation course be designed? How can learning objectives, activities, and assessments be meaningfully aligned in a simulation course?

Our framework is grounded in established pedagogical approaches and integrates, for the first time, these theoretical foundations into a cohesive structure explicitly operationalised for simulation education. We pioneer the implementation of the revised (Anderson & Krathwohl, 2001) Bloom's taxonomy (Bloom et al., 1956) in simulation education to support the formulation of clear learning objectives. Furthermore, we build on recent attempts to use blended learning (Low et al., 2021) and grading contracts (Liu et al., 2025) in simulation courses. Finally, we integrate constructive alignment, an outcome-based education model that aligns intended learning objectives, teaching activities, and performance assessment (Biggs, 1996), into simulation education. We propose a novel framework called Customise-Build-Align (C-B-A), which consists of the three pillars of constructive alignment and offers comprehensive guidance for designing a simulation course that includes learning objectives, structure, and assessment:

- **C**ustomise learning objectives for a simulation course (intended learning outcomes),
- **B**uild learning experiences for a simulation course (teaching and learning activities),
- **A**lign the learning activities and outcomes with assessment methods of a simulation course (assessment portfolio).

Our guidance is inspired by our unique blend of international experiences of teaching simulation, spanning different countries (i.e., the USA, the UK, and Austria), different scientific domains (i.e., business, computer science, life sciences, and engineering), and levels of higher education (i.e., undergraduate, master's, and doctoral students). This paper offers a novel contribution to simulation education and teaching practice by providing (i) a generic pedagogical framework for constructive alignment of learning objectives, activities, and assessments, (ii) essential building blocks of a simulation course, and (iii) a practical guide for simulation educators to apply the framework across simulation courses in different fields of study, educational levels, and national contexts.

The outline of this paper is as follows: Section 2 reviews existing literature on simulation education. In Section 3, we describe our proposed C-B-A framework for teaching simulation, including important building blocks of simulation courses. Subsequently, we discuss application examples from international simulation courses and compare them in Section 4. We conclude by discussing the implications of this work for simulation knowledge and practice in Section 5 and by outlining directions for future research on simulation education in Section 6.

2. Simulation education literature

Existing literature on simulation education includes course descriptions, examples, and best practices for teaching simulation. We supplement our review with a discussion of the literature on teaching with simulation, focused on the potential of simulation-based learning, gamification, and serious educational games, to provide a comprehensive picture of existing simulation education practice.

2.1. Teaching simulation

Course descriptions report on authors' experiences with online learning methods for teaching DES (Hunting et al., 2007) and ABS (Macal & North, 2013). Hoad and Kunc (2018) argue that teaching continuous and discrete simulation within one course requires a strong emphasis on problem formulation, verification and validation, and translation of simulation results into managerial decision making. Saltzman and Roeder (2013) report on teaching simulation in a college of business, focusing on the individual backgrounds of their students. Other authors compare the performance of student groups from computer science, statistics, and business backgrounds on a simulation task and highlight the importance of a broad educational foundation in model coding, data analysis, and problem-solving skills (Robinson & Davies, 2010).

Furthermore, particular attention has been paid to teaching specific simulation environments such as FlexSim for a course in business informatics (Binsztok et al., 2022) or Witness and Captivate for a logistics course (Tvrdon & Juraskova, 2015). Articles considering different countries compare simulation courses at universities in Spain, Portugal, and Ireland (Campos et al., 2020), report on implemented design principles for integrative modelling in simulation courses delivered in Canada and the USA (Giabbanelli & Mago, 2016), and share tips and strategies for teaching simulation based on their experiences as educators at universities across the USA (Freimer et al., 2004). Additionally, several panels at the Winter Simulation Conference discuss the best practices for teaching simulation (Altiok et al., 2001; Jacobson et al., 1994; Stahl et al., 2003), conceptual modelling (Van der Zee et al., 2010), and simulation model simplification (Van der Zee et al., 2018).

Skoogh et al. (2012) argue that structuring courses around clearly articulated intended learning outcomes, aligned learning activities, and coherent assessment criteria leads to improved simulation courses. They illustrate this with two examples of simulation teaching practice at the Chalmers University of Technology in Sweden and the University of Michigan at Dearborn in the USA, where course objectives in model building, experimentation, and communication are systematically mapped to project-based assignments, laboratory exercises, and reporting requirements. Garcia and Centeno (2009) outline early simulation course concepts for undergraduates. In Operational Research education, Lorig et al. (2025) provide a course design for agent-based simulation of social systems, Nylund and Lanz (2020) contribute interactive learning activities for the education of factory-level order-to-delivery processes, and Zhang et al. (2022) use constructive alignment for a course on management information systems.

Successful approaches to ensuring practical relevance in teaching simulation courses include:

- **Case studies and real-world projects**: Martin (2018) embeds a real-world simulation project for master's students in Business and Information Systems Engineering taking an introductory simulation course. Interactions with representatives of the engineering department of a logistics service company are integrated during the course, and at the end, students present their solutions to the company. Tako et al. (2020) employ a real-world ambulance service case study to teach undergraduate students collaborative conceptual modelling through facilitated group workshops structured around the PartiSim user guide. Setting simulation tasks based on real-world industry or research problems allows students to address complex, real-world challenges while developing professional skills. Standridge (2000) contributes a case-based teaching approach focusing on systems, organisations, operating strategies, material handling, and supply chain management to impart DES to manufacturing engineering students. Using case studies as a teaching method enables students to learn from existing simulation projects applied in real-world scenarios with industry involvement (Black & Chick, 1996).
- **Serious game-based simulation workshops**: Kogler and Rauch (2020a) report on advanced knowledge transfer, training methods, and decision support by involving stakeholders in workshops where industry professionals, policymakers, researchers, and students use a DES model of a wood supply chain to experience, discuss, and manage real-world challenges. The authors provide guidelines on how insights from workshop design, user interaction, and participant feedback can be integrated into the modelling process, with a focus on intuitive usability, visualisations, and animations. This helps to improve the reliability, suitability and credibility of simulation models from an educational perspective.

2.2. Teaching with simulation

The simulation-based education arena is concerned with learning through using simulation. Leigh et al. (2023) propose a roadmap for simulation in education, highlighting that simulation enables student engagement and encourages educators to adopt participatory education approaches (Angelini & Muniz, 2023). Pena-Miguel and Sedano Hoyuelos (2014) define gamification or serious games as the use of game thinking and game mechanics in an educational setting to encourage users to solve problems as part of their learning.

An overview of the effects of serious games is given by Giessen (2015), and positive impacts are highlighted in a literature review by Boyle et al. (2016). Deghedi (2023) reviews serious games developed in the USA (45%), Europe (34%), Canada (16%), and the Middle East (5%) and assesses them based on an introduced game complexity index. Systematic literature reviews of papers that use simulation-based learning in higher education offer evidence of its benefits in various educational settings. Vlachopoulos and Makri (2017) review articles on the use of games and simulation pedagogy in higher education. Asadi et al. (2024) offer an overview of the existing theoretical practice and advantages of simulation-based learning tools and review the use of simulation-based learning, such as simulation software, tools, and serious games in teaching IT and computing subjects in higher education.

De la Torre et al. (2021) review the role of simulation in teaching sustainability concepts for students' active learning and note that such approaches are not yet widely used despite their positive impact. Based on a review of recent works on simulation-based education, Campos et al. (2020) discuss its benefits in teaching and learning. These include enriched learning experiences through increased learner motivation, emotional attachment, knowledge construction, collaborative work skills, critical thinking, problem-solving, and decision-making. In addition, after a review of simulation-based experimental learning applications in industrial engineering education, Despeisse (2018) formulates suggestions for developers of serious games to align their designs with cognitive and affective learning outcomes in teaching. Kincaid and Westerlund (2009) stress the importance of educating simulation specialists so they can select, design, and implement training simulations appropriately. Simulation-based learning is also practical for non-simulation courses (McHaney, 2018) and high school education (Kilag et al., 2023), where DES is used to build simulators for experiential learning (Da Silva et al. 2014). A promising path for implementing simulations in education is to embed them in a blended learning concept, as Low et al. (2021) suggest, using a flipped classroom approach to positively assist students in their learning.

One widely used simulation-based game is the Beer game, which was developed at the MIT Sloan School of Management in the 1960s (Forrester, 2012) and adapted into further variants (Sterman, 2006; Sterman & Dogan, 2015). Other examples include the freely available Online Wood Supply Game (D'Amours & Rönnqvist, 2013), the Collaborative Logistics Game (D'Amours et al., 2017), the Transportation Game (Abasian et al., 2020), and the Virtual Wood Supply Arena (Fjeld et al., 2024). These games focus on teaching supply chain concepts such as hierarchical procurement and system capacities planning as well as fluctuations caused by bottlenecks and the bullwhip effect. Their application in serious game-based workshops allows learners to gain hands-on experience with real-world challenges of, for example, wood supply chains and to develop competencies for contingency planning (Kogler & Rauch, 2020b) and resilient logistics (Kogler, 2024).

The basics, procedures, and applications of gamification and serious games are discussed in a business context by Strahringer and Leyh (2017). Faria et al. (2009) reviews 40 years of business gaming, while Riedel and Hauge (2011) review games for industry to evaluate their support for skill development. Stapleton (2004) discusses the opportunities that serious games offer in education, as they enable a shift from a teacher-centred to a learner-centred educational approach that encourages deep learning, the development of problem-solving skills, and student engagement. Game-based learning also challenges educators, who need appropriate training to integrate interactive digital tools into their (in-person or online) lectures (Toquero et al., 2021). Guidance on creating serious games is available, such as that provided by Heidmann (2015). Furthermore, Van der Zee et al. (2012) contribute a framework for developing DES-based educational games, and Mestadi et al. (2018) introduce an architecture for serious game design.

2.3. Gaps in pedagogical literature

This literature review shows that a large body of research has examined teaching with simulation, including simulation-based learning, gamification, and serious games across a wide range of disciplines. These studies provide evidence of learner engagement, cognitive benefits, and the design of simulation-supported educational environments. In contrast, curricular structure and didactic principles of teaching simulation have received considerably less attention. Existing contributions mainly report on individual course experiences or isolated best practices, but do not offer an overarching pedagogical framework. Consequently, comprehensive guidance for structuring simulation courses across different higher-education contexts is missing. In response to the gap identified, we pose that there is a need for a flexible and generic framework to support simulation educators in designing aligned, transparent, and pedagogically grounded simulation curricula.

3. The Customise-Build-align (C-B-A) framework for simulation education

Our C-B-A framework provides a generalisable pedagogical approach that aligns learning objectives, instructional activities, and assessments to operationalise constructive alignment for simulation education (Figure 1). We introduce an intuitive three-step framework which ensures that:

- what students are expected to learn (**C**: Customise learning objectives for a simulation course, section 3.1),

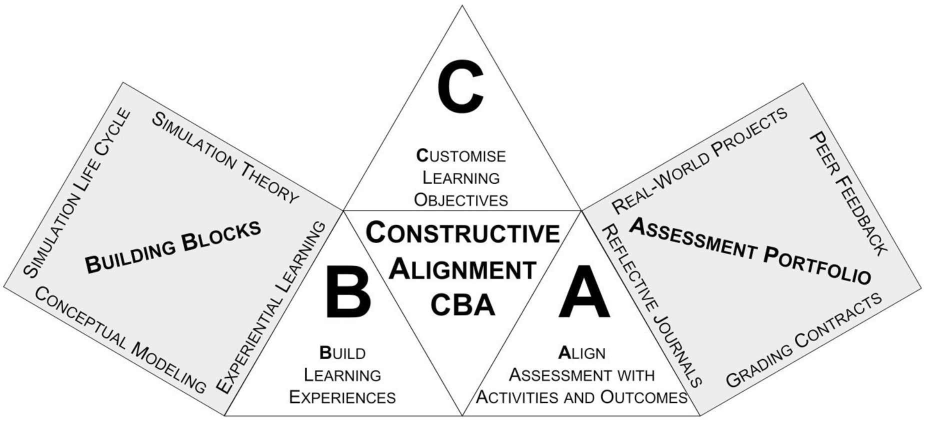

Figure 1. Visualisation of the C-B-A framework for simulation education.

Table 1. Framework for the formulation of learning objectives for simulation courses based on the revised Bloom's taxonomy, including sample action verbs for each category.

		Cognitive process					
		1. Remember	2. Understand	3. Apply	4. Analyse	5. Evaluate	6. Create
Knowledge	I. Factual	Define	Summarise	Use	Select	Determine	Compile
	II. Conceptual	Identify	Classify	Operationalise	Differentiate	Critique	Design
	III. Procedural	Recall	Explain	Carry out	Compare	Assess	Implement
	IV. Metacognitive	Recognise	Anticipate	Leverage	Deconstruct	Reflect	Formulate

- how they engage with the material (**B**: Build learning experiences for a simulation course, section 3.2),
- and how their learning is evaluated (**A**: Align the learning activities and outcomes with assessment methods of a simulation course, section 3.3)

are coherent and mutually supportive. The C-B-A framework supports simulation education in designing coherent, practice-oriented, and learner-centred courses to create motivating and engaging learning environments. It integrates a collection of clear learning objectives, key learning activities and methods, and a portfolio of assessment options adaptable for different educational settings, disciplines, and (academic) levels. These are critical aspects in a field characterised by iterative, hands-on, and problem-solving learning processes.

3.1. Customise learning objectives for a simulation course

The formulation of learning objectives for a simulation course is a challenging task. However, it is worth the effort because it helps educators and students to manage each other's expectations and ensure a successful learning process. While a small set (e.g., 5–10) of custom learning objectives per course are standard, we have formulated 24 generic learning objectives to provide a blueprint for simulation educators.

The learning objectives are structured according to the revised Bloom's taxonomy descriptors as defined by Krathwohl (2002), enabling visualisations of the learning objectives in two dimensions:

- the traditional knowledge dimension, with levels I-IV of factual, conceptual, procedural, and metacognitive knowledge, and
- the cognitive process dimension, related to hierarchically increasing levels of learner cognition (1–6):

  1. **Remember**: retrieving relevant knowledge from long-term memory
  2. **Understand**: determining the meaning of instructional communication
  3. **Apply**: carrying out or using a procedure in a given situation
  4. **Analyse**: breaking into parts to detect how they relate to another and to an overall purpose
  5. **Evaluate**: making judgements based on criteria and standards
  6. **Create**: putting elements together to form a novel, coherent, or original output

The two-dimensional structure allows us to devise our 24 generic learning objectives for simulation education, numbered I.1 through IV.6. Simulation instructors can tailor these objectives to their own courses using this structure as a guide. Table 1 summarises the revised taxonomy, with sample action verbs for each of the 24 categories. This is followed by sample learning objectives for each category.

I. Factual knowledge represents basic terminology and specific elements to be acquainted with for solving standard problems of a discipline:
   1. **Define** the life cycle processes for developing digital simulation models.
   2. **Summarise** the basic components of conceptual modelling.
   3. **Use** standard modelling categories to identify (simulation) model types.
   4. **Select** probability distributions for standard input characteristics.
   5. **Determine** data, expert, and stakeholder involvement in verification, validation, and credibility building.
   6. **Compile** key simulation terminology into a structured glossary.

II. Conceptual knowledge covers principles and models of interrelationships between categorised basic elements of a larger structure:
   1. **Identify** agents, entities, interactions among system components modelled in DES and ABS.
   2. **Classify** conceptual frameworks that integrate DES, ABS, and/or Machine Learning in hybrid simulation approaches.
   3. **Operationalise** conceptual guidelines for facilitating serious simulation games in workshop settings.
   4. **Differentiate** the influences of modelling techniques and input parameters on the key performance indicators of a simulation model.
   5. **Critique** the assumptions, strengths, and limitations of DES, ABS, and System Dynamics.
   6. **Design** conceptual models (e.g., business process models in BPMN 2.0) to visualise a practical problem setting at different abstraction levels.

III. Procedural knowledge consists of the know-how and skills to select and apply appropriate methods, algorithms, and techniques:
   1. **Recall** key steps in statistical analysis for managing and analysing input and output data in simulation studies.
   2. **Explain** procedures for designing, executing, and documenting the verification and validation of simulation models.
   3. **Carry out** a sensitivity analysis with repeated simulation experiments, parameter variations, and a warm-up period.
   4. **Compare** two real-world DES and ABS models according to their inputs, outputs, structure, assumptions, and system representation.
   5. **Assess** how different process improvement alternatives align with organisational goals.
   6. **Implement** simulation models in an appropriate software environment (e.g., AnyLogic, Simio, Simul8) to solve practical problems.

IV. Metacognitive knowledge involves cognition in general, strategic self-knowledge, and an awareness of one's own cognition:
   1. **Recognise** opportunities to leverage AI-assisted coding and modelling tools to enhance personal learning strategies and experience in simulation education.
   2. **Anticipate** how modelling assumptions, uncertainties, and data limitations influence the interpretation and communication of simulation results in managerial decision-making contexts.
   3. **Leverage** insights from simulation outcomes to formulate and justify alternative strategic improvement options across different problem settings.
   4. **Deconstruct** existing simulation models to uncover reasoning processes, modelling choices, and implicit assumptions guiding their structure and purpose.
   5. **Reflect** on how simulation results inform and constrain sustainable management decisions.
   6. **Formulate** self-directed simulation projects to solve practical problems and communicate the outcomes.

3.2. Build learning experiences for a simulation course

We identify four building blocks of a simulation course as the foundational components necessary for teaching simulation. These customisable building blocks form essential elements for simulation education integrating theory, methodology, and applied learning. We begin with simulation theory, emphasising the value of using digital models, distinguishing among different modelling approaches, and introducing core simulation methods. Next, the simulation life cycle outlines the iterative development, verification, and validation processes required to ensure credible and reliable models. Conceptual modelling is then discussed as a supportive step for designing simulation models, especially for students who are new to modelling. Finally, experiential and blended learning approaches are highlighted to demonstrate how practical, case-based, and competitive simulation exercises enhance student engagement and deepen their understanding of complex systems.

We identified these building blocks through a structured, iterative process combining (i) a review of existing simulation education literature including simulation education track panels at the Winter Simulation Conference, (ii) a synthesis of the authors' international teaching experiences, and (iii) cross-validation through course comparisons. This ensures that the resulting components are relevant and transferable across countries, disciplines, and educational levels.

3.2.1. Simulation theory

A solid foundation for teaching simulation theory is built on general modelling theory. This includes explaining the motivation for studying systems through experimentation with a representative model to avoid inefficient, unsustainable, dangerous, long-lasting, or costly trial-and-error approaches with real objects of the actual system. Additionally, fundamental information on the different types of models can be taught. Models can be abstract or physical, such as artificial or natural analogue simulation. Abstract models can be figurative (e.g., business process diagrams), verbal (e.g., discussion), or mathematical, such as analytical approaches (e.g., optimisation) or digital (computational) simulation.

A key distinguishing feature of digital simulations is that they incorporate both time and randomness, allowing them to model how systems evolve. Deterministic models do not contain random characteristics, whereas stochastic digital simulations can model uncertainties, probabilities, and distributions. Practical examples can illustrate that, in contrast to static approaches, dynamic simulation models account for changes over time, with state variables changing either continuously or at discrete points in time, and that even system rules can change over time. Students can be shown that simulation allows the construction of models that are as close to reality as desired by integrating stochastic elements, complex queuing systems, dynamic systems featuring nonlinear behaviour, time and causal dependencies, uncertainty, memory, non-intuitive interdependencies between variables, and a large number of parameters. In contrast to similarly-scoped analytical models, which may be intractable, the simulation model can be executed.

The next step in teaching simulation theory is to introduce the type(s) of simulation that will be covered in the course, such as DES, ABS, and System Dynamics. Students learn that with the DES method, the process flows of entities that use resources with specified attributes are controlled by events and modelled using characteristic elements such as sources, delays, queues, and sinks. The DES engine specifies the rules and logic under which the model operates. Depending on the audience and learning objectives of the simulation course, the simulation engine can be discussed in great technical detail or at a very abstract level. For example, computer science students could discuss the data structures required to maintain and manipulate the future event list, which may not be of primary interest for business students. Helpful guidelines for introducing the logic of a DES engine are provided by Banks et al. (2013) and Law (2024).

Furthermore, students learn that ABS provides suitable modelling possibilities when the behaviour of the overall system is unknown, and the behaviour of individual objects is known. It offers flexibility and is well suited for capturing heterogeneous agents with autonomous decision-making and their interactions. On the other hand, System Dynamics represents systems as closed causal loop structures of coupled, first-order nonlinear differential equations. It may be sufficient to explain characteristic elements of System Dynamics such as causal loop diagrams with positive or negative feedback loops, stocks representing the state of the system, as well as flows with change rates of this state. Finally, if more than one methodology is covered in the course, the instructor should highlight that the different simulation methods were developed largely separately, but powerful simulation software support allows their hybrid integration to exploit individual strengths and model a broad range of abstraction levels and planning horizons.

3.2.2. Simulation life cycle

The simulation life cycle (Robinson, 2014; Tako, 2015) consists of the generic steps of a simulation study: framing the project, conceptual modelling, model development, experimentation, and implementation. This is typically an iterative process with feedback loops for verification and validation to establish credibility in the model developed (Woletz et al., 2025).

Figure 2 summarises our updated model development process, highlighting the decision points for assessing the feasibility of the project plan, validity of the assumptions, the verification of the model, as well as the validation and credibility of the results. General project aims are defined in the framing stage and further specified during the conceptualisation. The conceptual model (Robinson et al., 2010) is translated into a simulation model in the development stage, which includes model coding, revising, and testing. In the experimentation stage, scenarios are designed and an appropriate number and length (e.g., including a warm-up period) of simulation runs for achieving robust results are predefined (Kleijnen, 1995; Law, 2024; Lorscheid et al., 2012;

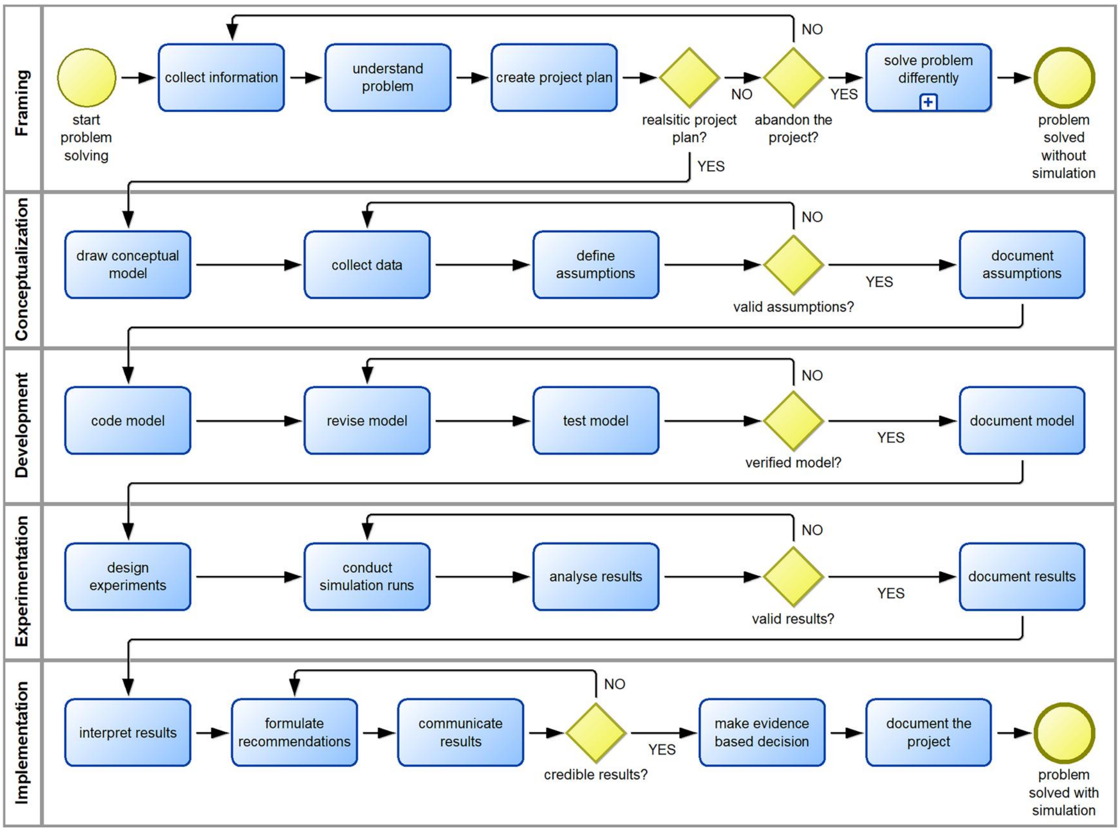

Figure 2. Key stages of a simulation study.

Ritter et al., 2011; Sargent, 2015). These simulation runs are followed by scenario, output data, and sensitivity analyses. Finally, the results are documented (i.e., reports, videos) and communicated (e.g., in workshops, presentations) to support real-world implementation by evidence-based managerial recommendations. Throughout this process, model verification and validation take place to ensure valid (Sargent, 2013) and credible (Law, 2022) decision support. From a model-theoretic perspective, verification and validation can be framed as relations among the reference model, research question, conceptual model, and simulation, emphasising the traceability of assumptions and constraints (Tolk et al., 2013).

It is essential to report transparently on the verification (i.e., extreme value parameterisation, structured walk-through, trace-driven debugging) and validation (i.e., comparisons with existing systems, expert estimates, literature data) methods used to establish credibility through expert and management involvement, live demonstrations, and stakeholder workshops (Woletz et al., 2025). Sound documentation of simulation projects (Kogler & Rauch, 2018) consists of detailed information on the following:

- data collection (i.e., literature, interviews, time studies, sensor data, and distribution fitting),
- simulation method (i.e., type, runs, period, software, abstraction level, and planning horizon),
- functionality (i.e., model logic, limitations, process diagram, visualisations, and modular design),
- and the case study setting (i.e., region, sector, scenarios, objectives, and key performance indicators).

Further comprehensive explanations on simulation modelling are provided by Law (2024), Robinson (2014), and Banks et al. (2013). For practical guidelines for specific simulation software, readers are referred to Smith and Sturrock (2025), Borshchev and Grigoryev (2025), and Mahdavi (2020).

3.2.3. Conceptual models

The next consideration when teaching simulation concerns how to help students design their simulation models. This is addressed by conceptual modelling. Conceptual modelling is one of the key stages in the simulation study life cycle (Robinson, 2008a). It consists of the process of extracting information about the real-world system and deciding what to include in the simulation model. This can be either an informal process or a formal one, the latter meaning that a well-documented and detailed report is developed, depending on project requirements. A formal document is normally a standard practice in industry, particularly when stakeholders are closely involved and a formal agreement is required in the early stages before proceeding with the simulation project.

The simulation conceptual model is an artefact, which is the outcome of the conceptual modelling process. It consists of an abstract description of the real-world system that will be, is, or has been represented in the simulation model (Robinson, 2008a). Robinson (2008a) defines the conceptual model as "a non-software specific description of the computer model, including the objectives, inputs, outputs, content, assumptions, and simplifications of the model". In other words, it defines the key elements of the real system to be represented in the simulation model.

Tolk et al. (2013) propose a modelling and simulation system development framework, which explicitly links requirements capture and modelling questions, conceptual modelling, and verification and validation within a unified development process. They distinguish between a reference model that aims for completeness and may accommodate multiple, even competing interpretations, and a conceptual model as a subset that forms the foundation for model implementation. This separation strengthens traceability from the problem situation and modelling questions to the simulation artefact, and provides a clear rationale for teaching conceptual modelling, verification, and validation as tightly coupled activities rather than isolated steps.

There is a concern that conceptual modelling is often ignored or misunderstood. When modelling a simple problem, we tend to intuitively conceptualise simulation models in our heads without documenting them on paper. Indeed, Tako and Robinson (2010) found that when asking expert modellers to build a simple model of the UK prison population, they rarely drew a diagram but developed the model directly on the computer. Expert modellers were intuitively thinking about what to include in the model, without the need to create detailed documentation of the model description on paper. An earlier study by Wang and Brooks (2007) followed the conceptual modelling activity carried out by expert and novice modellers and compared the differences in their modelling behaviours. They found that the expert modeller spent significantly more time on conceptual modelling compared to novice modellers for non-trivial systems. They also report that novice modellers spent little time understanding how the system worked and notice that they did not consider the model structure in the early stages of the study, often jumping straight to data collection with limited prior planning. Some developed the conceptual model at the same time as model coding, whilst others documented the conceptual model with a process flow diagram at the end of the study for the purposes of including it in their coursework report. Studies reporting on modellers' behaviour offer evidence that even though modellers may not formally document their models, it is a key step in extracting the model objectives and designing the simulation model. Indeed, conceptual modelling is considered more of an art than a science (Shannon, 1975). Novice modellers, in particular, would benefit from paying more attention to it, as it can help with planning and developing better quality models. There are negative consequences of ignoring conceptual modelling in large real-world projects, especially when more than one modeller is involved in developing separate parts of the simulation model.

Many authors have developed conceptual frameworks to guide the process of designing the simulation model (Balci & Ormsby, 2007; Kotiadis et al., 2014; Robinson, 2020; Van der Zee, 2010), and a dedicated book on conceptual modelling for DES is available (Robinson et al., 2010). Here we outline the conceptual framework developed by Robinson (2008b) that can be used for any type of problem. It prescribes the process of developing the main components of a conceptual model, which include the following:

- The modelling objectives describe the purpose of the model and simulation project.
- Model inputs consist of the experimental factors or changes that can be made in the model to observe their impact on meeting (or not) the modelling objectives.
- Model outputs are the results of interest from the simulation model with respect to the modelling objectives. They can help the modeller determine whether the modelling objectives have been achieved or identify reasons why the objectives are not being achieved.
- Assumptions and simplifications have different roles. Assumptions are introduced when there are uncertainties or beliefs about the real world being modelled, whereas simplifications aim to reduce the model scope to simplify the real-world system represented in the model.
- The model content describes the parts of the system included in the simulation model and at what level of detail. Often different visual tools are used for conceptual model representation, starting with simpler approaches such as process flow diagrams, activity cycle diagrams

(Brailsford, 2004), and other standard and notations such as SysML (Liston et al., 2010), Business Process Model and Notation (BPMN), and Event Graphs (Onggo, 2009; Schruben, 1983).

The BPMN 2.0 standard of the Object Management Group (2011) provides an intuitive flowchart notation for business process diagrams (Aagesen & Krogstie, 2015; Chinosi & Trombetta, 2012; Geiger et al., 2018). BPMN diagrams are an easy-to-use visualisation tool (see e.g., Figure 2) to communicate expert knowledge for designing, managing, and realising business processes to external stakeholders, widely applied across logistics, production, healthcare, cybersecurity, blockchain, AI, and the Internet of Things (Cimino et al., 2025). In the scientific literature, BPMN diagrams are used to conceptualise, explain, and illustrate simulation model internals (Kogler et al., 2020; Kogler & Rauch, 2019; Wagner, 2018) and analyse, improve, or redesign business processes (Windisch et al., 2013a, Windisch et al., 2013b, Scheuerlein et al., 2012). Furthermore, the visual syntax of process diagrams can be combined with the semantics of Event Graphs based on the Discrete-Event Process Modelling Notation for platform-independent visual simulation models (Wagner, 2024).

In summary, we believe that teaching conceptual modelling in simulation curricula is important, especially for students who are new to modelling, as it is a key model building block for developing relevant simulation models. Examples of teaching conceptual modelling in university and industrial courses are provided by Loper et al. (2012), Van der Zee and Holkenborg (2010), Pels and Goossenaerts (2007), and Figueras et al. (2014). Helpful examples to teach model conceptualisation are the fast-food restaurant case study (Robinson, 2017), the nursery parking problem (Robinson, 2012), and the outpatients' eye clinic case study (Robinson, 2015).

3.2.4. Experiential, AI-supported, and blended learning

Fostering experiential learning is essential in the field of simulation education, where abstract models must be understood in relation to real-world complexities to translate theoretical knowledge into practical competencies. One particularly innovative and impactful form of case-based experiential learning is participation in simulation-based competitions, such as the International Wood Supply Game Competition (Kogler, 2022), which we introduce here as an example of a transferable teaching format. This serious gaming format offers a playful yet demanding environment where students tackle the complexities of cross-company supply chain coordination. By managing dynamic financial, information, and material flows, participants apply leadership, communication, digitalisation, and analytical skills in an international setting. The competition also encourages the development of practical decision-support skills and fosters international collaboration among students and faculty alike. Furthermore, it is a creative way to kick off or wrap up a simulation course. Other experiential learning forms include simulation hackathons and design challenges (e.g., the Case Study Competition, Simulation Challenge of the Winter Simulation Conference). They are intensive, time-limited modelling tasks designed to cultivate applied skills, creativity, and collaboration under realistic conditions. These challenges mirror real-world time pressure and uncertainty, helping students develop modelling intuition, rapid prototyping skills, and the ability to justify quick decisions based on limited data.

Furthermore, AI tools offer multiple opportunities to enhance the teaching of simulation by providing individualised guidance and reducing the steep learning curve associated with modelling and coding. Systematic reviews of AI in higher education show that AI-based learning tools are particularly effective when supporting intelligent tutoring, personalised feedback, and formative assessment, rather than replacing human instruction (Luo et al., 2025). In simulation courses, generative AI (GenAI) can therefore act as an on-demand tutor that helps students articulate conceptual models, debug code, and reflect on assumptions, while instructors focus on higher-order reasoning and model credibility. These opportunities are complemented by advances in cloud-based simulation platforms and collaborative online tools, which allow students to jointly build, test, and iterate models in real time, to receive automated feedback, and to document their modelling rationale more transparently. When combined, AI assistants, cloud-based environments, and collaborative digital ecosystems create a scalable support structure that strengthens student engagement, enables more flexible learning pathways, and aligns well with the iterative, exploratory nature of simulation modelling, especially in blended learning settings.

A blended learning approach aligns with the principles of constructive alignment and supports the implementation of the essential building blocks of simulation courses. As a central component, a clearly structured course environment within a learning management system (e.g., Moodle) can serve as a digital anchor point for students. This online platform provides a clear course overview and continuous access to essential administrative information, tools for individual progress tracking, deadlines, and a wide array of multimedia learning materials such as screencasts, quizzes, tutorials, videos, and example simulation models. All eLearning modules can be released at the beginning of the term to enable individualised preparation based on prior knowledge (e.g., in computer science, coding, statistics), personal interests, and time availability.

A blended learning simulation course can be organised into weekly sessions, each consisting of three interrelated parts: self-study phases supported by eLearning modules, synchronous live sessions, and asynchronous online learning components. This structure promotes a balanced integration of autonomous learning and structured guidance throughout the course. While the synchronous sessions take place at fixed weekly times to foster routine and community, the asynchronous elements offer flexibility, as they can be completed within one week:

- Self-study phase: Preparation tasks can include theoretical reflection, reading assignments from textbooks and scientific articles, video lectures, screencasts, and repeatable multiple-choice self-tests. These tasks integrate foundational topics from the building blocks of simulation theory and the simulation life cycle to ensure that students grasp key concepts before the synchronous sessions.
- Synchronous session: This part focuses on instructor-student interaction, clarification of open questions, reflections on course content, and discussion of its practical implications, and can be conducted either in person or via video conferencing tools (e.g., Zoom, Microsoft Teams, Gather.Town). Active engagement is further supported through collaborative digital tools such as breakout groups, shared whiteboards, and live chat functions. Interactive survey platforms (e.g., TEDME, Kahoot, Mentimeter, Vevox) can be used to obtain feedback, facilitate real-time reflection, and energise online discussions. Synchronous sessions also include opportunities for students to present their own conceptual or simulation models, developed during asynchronous phases, and receive feedback from peers and instructors.
- Asynchronous elements: Self-paced components are designed to foster experiential learning through hands-on modelling tasks and guided problem-solving. The first half of the course can focus on individual or group-based conceptual modelling through the development of process models using BPMN tools (e.g., Bee-Up). In the second half of the course, students transition to building simulation models using advanced multi-method platforms (e.g., AnyLogic, Simio, Simul8). This phase follows the simulation model development life cycle, comprising project framing, conceptualisation, implementation, experimentation, and implementation. Students engage in model verification and validation activities, scenario and sensitivity analyses, and prepare final presentations. Structured support can be provided through targeted tutorials, screencasts, and technical guides to ensure accessibility for beginners, while advanced learners are challenged through additional exercises and reflection tasks.

This blended learning approach supports skill acquisition in modelling and simulation and enhances competencies in collaboration, communication, digital literacy, and problem-solving, which are key competencies for professional and scientific practice. Flexibility in time and place promotes autonomy, personal responsibility, self-efficacy, and active learning behaviours. Embedded experiential learning elements such as simulation-based case studies and competitions (e.g., International Wood Supply Game Competition, Simulation Challenge of the Winter Simulation Conference) can provide realistic challenges that motivate students and link theory to practice.

3.3. Align the learning activities and outcomes with assessment methods of a simulation course

Choosing suitable and effective assessment methods is a perennial question for simulation course instructors. Should there be a coursework assessment that students develop as the module progresses or, one final assessment at the end of the module? Should that be individual or group-based projects? One of the challenges in teaching simulation is the steep learning curve students encounter during the term. Especially if it is their first experience with simulation modelling or coding, it can be intimidating and lead to substantial anxiety, which, in turn, reduces the actual learning that takes place. Additionally, simulation tasks are often open-ended, in many cases without a straight right or wrong answer. The modeller needs to make many decisions, such as implementing simplifications along the way. Many students are not comfortable with this ambiguity, which in turn increases their stress and anxiety.

Simulation courses often use conventional assessment methods such as exams. Depending on a student's level of comfort with modelling and coding, self-study assignments can be time-consuming and stressful, in addition to exams being anxiety-inducing. High-stakes exams are formal assessments that have significant consequences for the student's final grade. While they can be useful for testing theoretical understanding under time constraints, they may be less suited to simulation courses, where iterative problem-solving and debugging are often essential learning outcomes. Students who otherwise understand the material may perform poorly due to non-content-related factors (e.g., test anxiety). We argue that courses focusing on hands-on learning and model building may more appropriately be evaluated based on the student's understanding of and competencies in simulation modelling.

Realising that there are errors or other changes that must be made is part of the learning process but can be challenging to assess on an exam. An exam can test whether students understand the theory of the iterative nature of the modelling process but is less well-designed to assess whether the student is able to implement it in practice. A small number of assessments done over the term is better suited to helping students stay current with the course and not fall behind. However, it carries the risk of over-assessment, which can be demanding for instructors. Mahmud and Salimian (2012) describe a redesigned assessment approach that does not allow students to advance to the next module until they have shown competency in the current one. While this approach fosters strong student engagement, it is labour-intensive for the instructor. Other assessment methods for simulation courses include:

- **Course participation:** assesses student engagement during lectures or laboratory sessions. In simulation courses, this can be particularly valuable for tracking how students interact with complex modelling decisions and peer feedback, fostering collaborative problem-solving.
- **Self-study and reading assignments:** assess independent learning and theoretical understanding. Students may be asked to write short forum posts or take a quiz on the reading. While helpful for reinforcing concepts and getting to know scientific simulation literature, this type of assignment ideally includes practical tasks to ensure that application skills are developed. For example, students can be asked to create conceptual models.
- **Quizzes:** low-stakes, possibly frequent assessments that help track students' ongoing understanding of modelling principles. This can reduce both test anxiety and give students an incentive to stay up to date with the course content. Students can be given the opportunity to attempt quizzes multiple times until they are able to show competence in the material.
- **Oral exams:** students defend their models in dialogue, which allows assessment of the depth of understanding and modelling rationale. This method allows instructors to probe students' reasoning behind design decisions, such as why certain entities, events, or rules were included, and how changes affect system behaviour.
- **Presentations:** students articulate their modelling process and defend their design decisions in front of an audience. This is highly relevant in simulation, where transparency and the justification of assumptions are central to model credibility, as is the ability to present results to stakeholders.
- **Group work:** students tackle complex modelling tasks collaboratively. In simulation courses, group work reflects real-world modelling practices and supports peer learning, especially when projects are too large or open-ended for individual students.
- **Projects:** extended, often open-ended tasks that require applying course content to build, test, and refine a simulation model. Projects are particularly well suited for simulation courses, as they allow students to demonstrate mastery of the full modelling cycle from conceptualisation to analysis. Projects may be conducted individually or in groups (Hoad & Kunc, 2018).
- **Reflective journals or learning portfolios:** students regularly write about what they did, why they made certain modelling decisions, what challenges they faced, and how they resolved them. In simulation courses, this metacognitive activity helps students develop a deeper understanding of the modelling process by encouraging them to think critically about simplifications, parameter choices, and problem-solving strategies, especially when dealing with incomplete or ambiguous real-world information.
- **Peer assessment:** students evaluate each other's work using predefined criteria. This promotes critical reflection and collaborative learning, especially in group projects. By reviewing the assumptions, logic, or code of their peers' models, students deepen their understanding of modelling trade-offs and are exposed to alternative problem-solving strategies.

While these methods are straightforward and perceived as "fair and well-known", there are challenges (e.g., performance bias, subjectivity, inconsistency, stress, limited scope and coverage, coordination effort, unequal contribution/workload, inflexibility) associated with each of them, particularly depending on the type and structure of the course.

An innovative alternative, but little-known, assessment method is grading contracts. These have long been used in composition courses as a means of acknowledging the work students put into the course, allowing them to focus on the purpose of the work and active learning, rather than on how the work will ultimately be evaluated (Inoue, 2019). Grading contracts, also referred to as labour-intensive contracts, are assessment arrangements in which the student and instructor agree at the beginning of the course on the number and type of tasks to be completed during the term. The final grade is then determined by the extent to which the student fulfils these agreed-upon activities. For example, rather than a summative assessment of a final paper, students may be evaluated for turning drafts in on time, incorporating feedback into subsequent drafts, and reflecting on the changes they have made. Similar approaches have been used in mathematics and the sciences (e.g., Cangialosi, 2018; Hiller & Hietapelto, 2001). Liu et al. (2025) discuss the use of grading contracts in an undergraduate simulation course. Since the focus is on the work done by the student, rather than the final output, grading contracts are well suited to training students in the importance of the iterative process of building and using simulation models. Rather than penalising students for not "getting it right" the first time, the focus is squarely on the need for careful evaluation and revision of the model. Trying different modelling approaches can be rewarded rather than penalised when one or more of them inevitably do not work out. Quizzes, exams, and self-study assignments can still be used as part of the assessment process if desired.

AI challenges the integrity of assessment, even when authentic tasks are used, because AI-generated submissions can pass expert scrutiny and detection tools remain unreliable (Kofinas et al., 2025). Rather than responding by reverting exclusively to high-stakes, proctored exams, recent studies argue for assessment designs that emphasise higher-order learning outcomes, evidence of process, and transparency about how AI is used (Weng et al., 2024). We explicitly recommend integrating critical AI literacy into simulation courses: students should be made aware of typical failure modes such as hallucinations, outdated or unverifiable information, hidden biases, and overconfident but incorrect outputs, as synthesised in current overviews of large language model risks and mitigation strategies (Sakib et al., 2024). When assessment focuses on portfolios, reflective accounts of modelling decisions, oral defences, and documented iteration histories, and when students must explicitly justify whether and how they have used AI tools, simulation educators can maintain academic integrity and make constructive use of GenAI-rich learning environments.

As GenAI becomes mainstream in professional practice, employers are likely to expect AI-literate graduates. Accordingly, simulation educators have a critical role in designing authentic assessments that integrate AI meaningfully into their courses. GenAI can be used as a tool for developing model code as well as for writing a report with varied success (Akhavan & Jalali, 2024; Håkansson & Phillips-Wren, 2024; Monks et al., 2025). In a similar way to process-oriented assessment and grading contracts proposed above, we posit that GenAI can be effectively embedded within the curriculum, pedagogy, and assessment strategies. Examples include tasks requiring students to critically evaluate models developed with and without AI, reflective analyses of the modelling process supported by evidence of AI use, and coaching conversations with AI tools to guide students through a decision or problem-solving task. In conclusion, the assessment methods described in this section work equally well when using AI-tools, when supported by well-designed prompts and scaffolding strategies, and dedicated guidance by simulation tutors.

We encourage instructors to follow a portfolio assessment approach combining various artefacts into a coherent body of work, documenting skill progression and iterative learning over the term, taking inspiration from grading contracts. This format is particularly valuable in teaching simulation, as it captures the full life cycle of student work, from initial model sketches to final reports, highlighting the progression of their learning (Schreiber et al., 2016) in both technical and conceptual skills. Self-assessment and goal setting should be applied to motivate students to reflect on their own progress and set learning objectives. This fosters ownership of learning, strengthens metacognitive skills, and helps identify personal development areas. In simulation courses, this enables students to recognise which aspects of model development (e.g., coding logic, conceptual modelling, experimentation) require further attention and improvement. Group work, peer assessment, and interactive presentation formats further make modelling decisions and assumptions transparent while fostering collaboration and communication skills. Portfolio assessments emphasise the sustained work students undertake throughout the semester and thus align philosophically with the principles of continuous engagement and iterative improvement.

4. Application examples in international simulation courses

The comparison of nine simulation courses from Austria, the UK, and the USA gives an overview of the international variety in simulation education in terms of level, length, area of study, and focus. It draws learnings from award-winning courses and combined decades of experience teaching simulation to showcase the cultivation of student competencies. In our courses, we ensure a fair workload for students and educators, while at the same time engaging students in the learning experience and maintaining high motivation and positive affect. We provide examples of how elements of the building blocks and our framework have been implemented in different simulation course settings.

4.1. Simulation course comparison

Table 2 compares nine different simulation courses at seven universities. It shows challenges such as the heterogeneous prior knowledge of students due to different academic foci, as well as exciting opportunities such as the suitability of teaching simulation in different study programs at diverse universities across the world. The courses were purposively selected based on three criteria: (i) they focus on teaching DES and/or ABS in higher education; (ii) they represent a variety of academic levels (bachelor's, master's, PhD) and disciplinary orientations (engineering, business, life sciences, and computer science); and (iii) they are taught by the co-authors or close collaborators, ensuring access to detailed pedagogical and structural information for reliable comparison.

4.2. Simulation course descriptions

In this section, we provide further insights into the courses listed in Table 2 and show how they align with the C-B-A framework. We show how the learning objectives for the courses are tailored to the students and the course level ("Customise"), how the course content is designed ("Build"), and, finally, how students' learning is assessed ("Align"). Integrating case studies into the curriculum provides students with a meaningful experiential learning opportunity for applying simulation methods to authentic problems, thus enhancing engagement, relevance, and deeper understanding. We present three illustrative case studies that demonstrate the practical application of simulation in wood logistics, production, and healthcare transport. These examples are intended to inspire instructors seeking to implement similar approaches. In line with our framework's emphasis on motivation, collaboration, and real-world relevance, these case studies exemplify how simulation education can be both rigorous and engaging.

4.2.1. Austria

Two simulation courses at the BOKU University and the University of Applied Sciences Campus Vienna were chosen to portray simulation education in Austria. At the BOKU University, all students are educated in basics of technology, natural sciences, and economics. Students in the Wood Technology and Management master's programme can choose a specialisation module in Advanced Planning and Simulation. Most students build on basic BPMN and business process reengineering knowledge acquired during their bachelor's studies (a 3-ECTS Business Process Modelling course) and also take a Business Management course in the same semester, where they are trained through game-based simulation workshops to participate at the International Wood Supply Game Competition.

In the Business Process Simulation course, students acquire theoretical and practical simulation knowledge. Typical learning objectives ("C") cover the cognitive process dimension applying (3), evaluating (5), and creating (6) to cultivate target conceptual (II) ("Design conceptual models to visualize a practical problem setting at different levels of abstraction"), procedural (III) ("Carry out a sensitivity analysis including repeated simulation experiments, parameter variations, and warm-up period", "Implement simulation models in an appropriate software environment to solve practical problems"), and metacognitive (IV) knowledge ("Reflect on how simulation results inform and constrain sustainable management decisions").

Learning activities ("B") include simulation theory and the life cycle, conceptual modelling as well as blended-learning elements. Following a research-led teaching approach, they focus on reading and discussing the latest literature on discrete simulation modelling within the wood supply chain, which was mainly driven by researchers at BOKU University (e.g., Holzfeind et al., 2021; Kogler, 2020; Kogler & Rauch, 2018, 2023; Scholz et al., 2018, 2021). Practical course elements are based on the building blocks of the simulation life cycle to deepen their skills in conceptual modelling. The course engages students in experiential learning through case studies on production, transportation, logistics, and supply chain management that are either based on current research projects or practical problem settings from industry introduced by graduates in management positions.

The Wood Stockyard Simulation Case Study represents a typical problem scenario in the field of natural resources management and is well suited for showcasing simulation education in Austria. Roundwood storage plays a pivotal role in enhancing the sustainability and resilience of forestry

Table 2. Comparison of simulation courses teaching Discrete-Event Simulation (DES), Agent-Based Simulation (ABS), and Business Process Model and Notation (BPMN) in Austria, the United Kingdom (UK), and the United States of America (USA).

Country	University	Background	Program	Course	Number of students	Topics	Software	Assessments
Austria	BOKU University	Technology and Natural Resources	Master: Wood Technology and Management	Business Process Simulation	15	Simulation theory and practice for supply chain management, production, transportation, logistics	AnyLogic (ABS, DES), Bee-Up for BPMN	Collecting points based on a portfolio assessment approach including self-study and reading assignments, simulation projects, presentations, group work, reports, oral exams
Austria	University of Applied Sciences Campus Vienna	Life Sciences	Master: Bio-technological Quality Management	Process Modelling and Simulation	25	Simulation theory and practice for healthcare, quality and laboratory management, chemical and pharmaceutical production processes	AnyLogic (ABS, DES, System Dynamics), Bee-Up for BPMN	Collecting points based on a portfolio assessment approach including self-study and reading assignments, simulation projects, presentations, group work, reports, oral exams
UK	Loughborough University	Business	Bachelor: Business and Management	Simulation for Decision Making	35	Role and applications of simulation models in managing business dynamics, life cycle for developing and using models, verification and validation	Simul8 (for DES) and Stella (for System Dynamics), NetLogo (ABS)	Coursework assignments: group simulation-based modelling report, individual essay comparing System Dynamics and DES
UK	Nottingham Trent University	Business	Master: Management	Prescriptive Analytics for Decision Making	60	Introduction to simulation, alternative modelling approaches, conceptual modelling, modelling variability, data analysis	Simul8	Individual coursework assignment
UK	National Course in Operational Research (NATCOR)	Operational Research	PhD: Business, Maths, and Operational Research	Simulation	40	Principles of simulation, modelling process, random sampling, verification and validation, output analysis, experimental design	Simul8	Multiple-choice exam
UK	Brunel University London	Computer Science	Bachelor: Business Computing	Business Analysis and Process Modelling	50	Business analysis, static modelling, process modelling, process improvement, impact of process change	BPMN, Simul8	Coursework assignments and exam
UK	Brunel University London	Computer Science	Bachelor, Master, and PhD: Computer Science	2-Day Simulation Workshop	30	Conducting simulation project	Simul8, SimPy, NetLogo, Repast Simphony, Repast4Py	Formative feedback
USA	San Francisco State University	Business	Bachelor: Business Administration	Computer Simulation	25	Simulation theory and practice, input and output analysis	Excel, SIGMA, Arena	Self-study assignments, quizzes, presentations, reports, final project, participation, peer evaluation
USA	University of California, Berkeley	Engineering	Bachelor: Industrial Engineering	Simulation for Enterprise-Scale Systems	70	Simulation theory and practice, input and output analysis	Excel, SIGMA, Simio	Self-study assignments, quizzes, presentations, reports, final project, participation, peer evaluation

supply chains, particularly when facing challenges in harvesting, transport, and processing. As intermediate buffers, stockyards regulate material flow along the value chain, thereby stabilising supply volumes and mitigating market fluctuations (e.g., due to windstorms or bark beetle infestations). Consequently, advanced simulation-based decision support is needed to enhance process efficiency and time management, maintain wood quality and value, lower emissions, and mitigate truck driver shortages (Kogler et al., 2026; Zamora-Cristales et al., 2026). Students analysed interviews and surveys conducted with wood value chain managers that revealed the critical problem setting of unknown transport durations and costs due to high queuing times, limited loading/unloading space, and a bottleneck in transport capacity after salvage wood crises (for further information refer to Kogler et al. (2024) and Kogler et al. (2025)). This problem setting was analysed in the Business Process Simulation course, where student teams developed hybrid DES and ABS models to provide simplified decision support. The processes were documented in BPMN 2.0 with the Bee-Up modelling tool and the simulation model was implemented in the Java-based simulation software AnyLogic.

Students are graded ("A") based on assignments, oral exams, and presentations of their hybrid DES and ABS simulation projects. These experiences encourage students to use a simulation approach for their master's theses, carried out within scientific research projects or in cooperation with external partners from industry. In the course evaluation, students highlighted the clarity of expectations ("C"), noting that "the learning objectives were clearly stated and easy to follow," recognised the coherence of the experiential learning design ("B"), describing how "the examples and explanations built logically on each other," and acknowledged the fairness and transparency of assessment ("A"), noting the "comprehensible evaluation criteria" and "supportive guidance throughout the assignments."

At the University of Applied Sciences Campus Vienna, students study part-time for a master's degree in Biotechnological Quality Management. This allows students to build on their everyday technical and management experience in evening and weekend courses. The second of four study terms focuses on Operational Research with subjects such as simulation, statistics, optimisation, Six Sigma, Lean, and Kaizen. The Process Modelling and Simulation course is, at 5 ECTS credits, the most comprehensive and elaborative course of the entire degree programme. It has been redesigned as an entirely online blended-learning course, a transformation that has been rated extremely positively in student evaluations, awarded by the university, and nominated for Austria's State Award of Teaching. An additional intranet resource now serves as a reference point for other instructors seeking guidance on how to redesign their own courses based on blended-learning principles.

The redesign of the course demonstrates clear improvements across all C-B-A components. Newly structured learning objectives ("C") contributed to a measurable rise in student interest from pre- to post-course surveys, enhanced learning experiences ("B") were reflected in substantial gains in self-reported knowledge levels, and aligned assessment practices ("A") were evidenced by excellent evaluation scores for clarity, structure, and communication.

In the first half of the course, students study simulation theory and focus on conceptual modelling with BPMN to design, improve, and reengineer practical processes at different abstraction levels. Here, the focus is on understanding factual (I) knowledge ("Summarize the basic components of conceptual modelling") and creating conceptual (II) knowledge ("Design conceptual models to visualize a practical problem setting at different abstraction levels"). In teams of two to four students, they complete the term challenge, where they solve and present practical process problems from their companies. In the second half of the course, students focus on the simulation life cycle to build DES, ABS, and System Dynamics models. Students master case studies on the spread of infectious diseases, hospital utilisation, vaccination, and test centre capacities supported by scientific literature on verification and validation, simulation optimisation, and the integration of simulation and Machine Learning. Typical learning objectives in this part of the course cover the cognitive process dimension understanding (2) and evaluating (5) for procedural (III) ("Explain procedures for designing, executing, and conducting verification and validation of simulation models", "Assess how different process improvement alternatives align with management goals") knowledge. Compared with more theoretical simulation courses at other universities, these part-time students with work experience benefit from the application-oriented simulation course and build advanced simulation models for real-world decision support.

4.2.2. United States of America

We discuss two undergraduate, upper-division simulation courses from the United States. The first course is taught in the business school at San Francisco State University, where most students have not had any previous exposure to coding. It is in a list of courses from which students select a certain number, depending on their major. The prerequisites for the course are business statistics and introductory information systems. There are several course objectives ("C"). Students should learn the fundamentals of computer simulation, at the conceptual (II) and procedural (III) knowledge levels, where they should be able to understand (2) ("Classify different approaches for simulation modelling") and to create (6) ("Implement a Monte Carlo simulation or DES model to address a business problem") in the cognitive domain.

We use the simulation theory, simulation life cycle, and experiential learning building blocks ("B"). Students begin the course by adding randomness to a simple, deterministic inventory model in Excel. After several weeks of Monte Carlo simulation, we move on to DES using SIGMA to understand the fundamentals of how simulation engines work and different components of the system interact. Towards the end of the term, students are introduced to Arena as an example of typical commercial software. They cover a module on input analysis, discussing sources of data and methods of data collection, as well as distribution fitting. In the module on output analysis, students learn about run control and basic concepts behind experimental design, time permitting. Students spend part of each course building models or experimenting with existing models.

Students are evaluated ("A") using a grading contract based on their work on weekly quizzes, self-study assignments (model building and experimentation), and a final project. For the project, students work in groups to apply simulation for a business problem. Throughout, students develop their presentation skills (three presentations) and writing skills (five reports) to practice communicating technical material with possibly non-technical stakeholders. They also practice providing constructive feedback to peers on presentations and group participation. As a final step for the grading contract, they do a self-assessment of their work over the course of the term and of what grade they believe they earned in the course. Their actual grade is not tied to what they believe they should get, but rather to the work they completed over the course of the term. The purpose of the grading contract is to encourage students to lean into the iterative nature of doing simulation analysis (see Figure 1) rather than worrying about not immediately finding the "right" answer. The emphasis is on the hands-on work of building models and the final project, though students are also held responsible for lower-order knowledge via weekly quizzes.

The second course is offered in the College of Engineering at UC Berkeley, where students must complete three courses in statistics/stochastic processes before taking the simulation course. In addition, they have had at least a semester of coding experience. While the setup of the course is the same as for the business students, the engineering students are able to tackle much more complex simulation challenges, having a stronger technical background knowledge than their business-school counterparts. As a result, less time is spent on learning objectives in II/2, and much more time is spent trying to achieve mastery in III/6. At the time this course was taught, we were not using grading contracts, so students' course grades were based on traditional weighted average calculations. The weights were chosen to emphasise the hands-on experiences in the course, and the grading focused on the thought processes behind the work and less on the final answer. On their final quiz, students were asked to reflect on their experience in the course, e.g., "What was the most important thing you learned in this course?"

A typical Production Process Case Study that needs to be simulated to improve workflows involves at least three machines that require a single worker to load and unload them. For example, a semiconductor manufacturing process may have a subprocess with a cluster of machines loaded and unloaded by a robot. The question is how many machines are required in the cluster to provide a certain throughput, as well as what type of robot is needed to ensure it does not become the bottleneck. At its simplest, there are no buffers after the machine, so the machine remains blocked if the robot is unavailable for unloading. The model can be made arbitrarily more complex by including buffers, load balancing, timers, or any number of other system characteristics. The scenario can be used to illustrate abstraction, as the same model logic applies whether there are three physically separate machines, or a single machine with three processing chambers (or whether it is a person or a robot doing the loading and unloading). This example provides a showcase of how different simulation packages can require a significantly different amount of effort from the modeller. When developing the model from scratch using the DES package SIGMA, students must first consider which events are required to model the system. They must then determine how different events occurring in the system can trigger other events. To avoid phantom servers or other undesirable phenomena, students must apply critical thinking and attention to detail. By contrast, developing the same model in Arena or other similar packages is almost trivial, as the software is pre-programmed to account for these details. The modeller can be prompted to think about different aspects of the system by the options available when entering information into the pre-programmed blocks. On the other hand, the perspective taken by the two approaches is quite different, as one focuses on the events underlying the system's dynamics, while the other is concerned with the path individual jobs take through the system.

4.2.3. United Kingdom

We describe five courses from the United Kingdom that span doctoral-level, final-year undergraduate, and postgraduate courses at Business and Computer Science departments.

The NATCOR Simulation course is offered on a biannual basis to PhD students and early-career researchers studying Operational Research. The module is a week-long residential course attended by PhD students and early-career researchers from Europe. The course aims ("C") to provide students with a general understanding of the mathematical and statistical principles of stochastic simulation modelling, and as such, focuses on the metacognitive (IV) knowledge dimension and the remembering (1), understanding (2), applying (3), and analysing (4) cognitive processes. Therefore, the main building blocks ("B") used include the simulation life cycle, conceptual modelling, and experiential learning through building simulation models and performing statistical analysis. Self-study materials such as book chapters and readings are provided for students to read before attending the course, which provide foundational knowledge for the synchronous part of the course. As students are self-motivated, this is offered as a voluntary task that is not assessed. Based on our observations, a large proportion of students complete it. An asynchronous element, to expand on the week-long synchronous live lectures, is also offered in which students are given extension tasks that they complete in their own time on a voluntary basis. By the end of the course, students are expected to comprehend the alternative simulation methods and the requirements for simulation studies, gain skills in using simulation computer packages, understand the nature of, and approaches to, input data modelling, and to analyse the output from a simulation model using appropriate methods. Students are assessed ("A") on the last day of the course via a multiple-choice test. The course is consistently rated very positively by the students, with an average score of 4.6 out of 5. Students comment particularly highly on the structure of the course ("B") and the social dimension resulting from its residential, one-week, face-to-face format, which brings together PhD students from across the UK and Europe. They also report that the course is highly beneficial for their doctoral studies and comment positively on the clarity of the learning objectives ("C").

The Simulation for Decision Support course was offered to final-year (third- year) undergraduate students studying business and management degrees at Loughborough University. The module is an optional module chosen by a range of students primarily from Management Science, Finance, International Management, and Management programs. The module offers 20 contact lecture hours and five hours of practical laboratory sessions over a 12-week term. The building blocks ("B") of the course consist of the synchronous live sessions, which offer students experiential learning opportunities through practical exercises working in groups and individually in practical laboratory sessions. The learning experience is expanded with asynchronous self-study tasks, which form part of the course assessment, where students work in groups or individually.

The aim of this module is to provide students with a critical appreciation of how the dynamics of the environment in which organisations work impact on their performance, to develop hands-on skills in modelling and simulation as an aid to decision-making, and to using simulation computer packages. Typical learning objectives ("C") include the cognitive process domain of applying (3) and evaluating (5) to develop primarily procedural (III) ("Carry out the translation of real business problems into simulation models") and metacognitive (IV) knowledge ("Reflect critically on the relevance and use of simulation in specific management and business situations").

The Ambulance Service Case Study is an example of a case study that has been used as a hands-on modelling exercise encouraging students to work in groups, analyse the problem, and identify solutions using facilitation techniques (Tako et al., 2020). The case describes an ambulance service system, that faces a high number of calls and resourcing issues, which affects its ability to respond within expected response time targets. When answering a call, the operators triage the call based on the severity of patients' condition to decide on the route to be followed. Incoming calls are classified as emergencies (life-threatening), urgent (non-life-threatening), and non-urgent. Some urgent and non-urgent calls are redirected to the Clinical Assessment Team (CAT) for re-evaluation and treatment may be provided over the phone. For the rest of the calls, an ambulance is dispatched and the patients may be transported to the local accident and emergency department (ED) or to alternative care services in the community. In some cases, the ambulance crew provides clinical treatment on the scene and the patient may not need to be conveyed to ED. This helps to reduce avoidable conveyances to ED and release ambulance resources. The management team thinks that many patients are unnecessarily being taken to ED and is examining the option of increasing CAT intervention with the view to reducing ambulance use and releasing resources for patients that require emergency ambulance transport. Three alternative solutions are considered: keeping the percentage of CAT intervention the same at 30%, increasing it to 40%, or further to 50%. Students are asked to experiment with the models and to study the findings against specific targets of the ambulance service, including response time targets, costs, and ratio of patients transported to the accident and emergency department compared with those treated in the community. They work in groups to assess the outcomes of different options and present their recommendations to the course and instructors.

Students are assessed ("A") with two separate coursework assignments. The first is a group exercise in which the students apply their modelling skills to develop a model of a real-world system of their choice to solve a specific problem, using simulation software (Simul8). They then reflect on the outcomes and assess the suitability of their results and recommendations to managerial decision-making. The second assignment consists of an essay-type assessment where students use cognitive processes of analysing (4) and evaluating (5) to assess and reflect on the application of modelling and group processes using materials shared in lectures, literature sources, and their own experience of group work during the group activities. The course receives very positive feedback from students in the end-of-year evaluations. Students note that the course differs markedly from other modules they take and offers numerous opportunities for active participation. They particularly commend the clarity of the learning objectives ("C"), the extent to which the assessment effectively synthesises the module ("A"), and the balanced integration of technical and practical experience with theoretical learning, enabled by the combination of learning activities ("B").

Prescriptive Analytics and Decision Making is offered to business students studying a master's degree in Management on the Business Analytics pathway at Nottingham Business School, which prides itself on being a leader in the sector, offering personalisation and an experiential learning approach to students. Students learn about different prescriptive modelling methods, of which simulation is taught in six contact hours, consisting of four hours of lectures and two hours of practical labs. The latter include simple hands-on exercises for the students to create models in a simulation software (i.e., Simul8). Prior to attending the module, students complete pre-course materials, consisting of videos and reading materials introducing simulation and application examples. Students complete a multiple-choice test, which accounts for 10% of their total grade and is completed by the second week of the module. The module is taught to business students at a primarily introductory level and hence the learning objectives (C") include the cognitive processes of understand (2) and apply (3), focusing primarily on the conceptual (II) ("Classify appropriate decision modelling methods"), and procedural (III) knowledge dimensions ("Carry out the formulation of management decision problems with appropriate models"). The main building blocks ("B") are simulation theory on variability, alternative simulation approaches, the simulation life cycle, and conceptual modelling to ensure an introductory level. The assessment ("A") task tests students' basic skills to design a simple simulation conceptual model aimed at supporting an imaginary food business to solve a real-world problem of their choice. The students are asked to pick a management decision that would be suitable to be solved using DES and to justify their choice. This task is considered suitable for an introductory level module for master's students.

The Business Analysis and Process Modelling course is taught in the second year of the bachelor's programme in Business Computing at Brunel University London (Kashefi et al., 2018). The course is delivered in two parts. The first part focuses on using static modelling to understand business process improvement. The aim of this part is to provide students with the fundamental knowledge of process modelling and understanding of how it supports business process improvement. The second part focuses on dynamic modelling and simulation-based experimentation. In this part, students learn how to translate a static process model into a DES model and how to perform experimentation with business process improvement scenarios.

The learning objectives of the course ("C") align primarily with the cognitive process domains of understanding (2), applying (3), and evaluating (5) and address factual (I) ("Summarize the concepts, principles, and perspectives that underpin business analysis and the development of associated models"), conceptual (II) ("Operationalize business analysis requirements into conceptual models that capture relevant concepts, boundaries, and relationships underlying the problem"), and metacognitive knowledge (IV) ("Reflect critically on issues and problems that arise when representing organizational processes and knowledge, and provide reasoned ways for how to resolve them").

The module is taught across two semesters and includes 16 hours of theoretical instruction in the form of tutor-led interactive lectures and 36 hours of practical laboratory exercises supported by faculty and teaching assistants. The building blocks ("B") covered in the lectures include simulation theory and the simulation life cycle. The laboratory sessions include topics in conceptual modelling and experiential learning. Students learn the fundamental principles of process modelling as well as develop a practical understanding of translating real-world business processes into static process models using BPMN. In the first part of the course, students develop an understanding of levels of abstraction and are able to identify interactions between business entities. The dynamic modelling part is taught using DES software. Simul8 for Education is used for practical tasks in the dynamic modelling component. Here students learn how to translate a BPMN-based static model into a dynamic DES simulation model. They experience the whole simulation life cycle and understand how to perform experiments in simulation and critically evaluate outputs from different experimental scenarios.

The learning objectives are assessed ("A") through two coursework assignments and an end-of-year examination. Both coursework assignments are individual and complementary. Students are given a business scenario, and are required to analyse, identify problems, and suggest business solutions. In the first assignment, students produce a static process model (BPMN) analysing the "as-is" system and suggest improvements by modelling improvement in a "to-be" model. The second assignment deals with dynamic modelling where students translate their BPMN model into a DES model using Simul8 and conduct experiments using "as-is" and "to-be" models. For both coursework assignments, students submit corresponding reports where they provide model documentation and critically evaluate the experimental results. The static modelling report accounts for 20% of the overall module grade and the dynamic modelling report accounts for 30% of the overall grade. The end-of-year exam assesses students' overall understanding of the building blocks and accounts for the remaining 50% of the overall module grade.

Undergraduate and master's students at Brunel University London have the option to conduct simulation projects for their dissertation (Taylor et al., 2014). The learning objectives ("C") of the intensive two-day simulation workshop include cognitive processes in the domains of understanding (2) and analysing (4) with the aim of providing an overview of factual (I) and conceptual (II) knowledge. To support students who choose to use simulation modelling in their projects, we deliver two-day workshops on DES and ABS. The first day is dedicated to the theoretical aspects of a simulation study and the theoretical concepts that underpin DES and ABS. These cover aspects of simulation theory and simulation life cycle as building blocks ("B"). On the second day, we introduce available tools for DES and ABS and brief practical tutorials for commercial and open-source simulation software, such as Simul8, SimPy, NetLogo, Repast Simphony, and Repast4Py. On the second day, we cover aspects of conceptual models and experiential learning building blocks ("B"). The materials are delivered in 50-minute sessions. Students receive formative assessment ("A") in the form of interactive feedback. At the end of each session, we hold a ten-minute feedback loop where students receive peer and tutor feedback.

5. Discussion

It is essential to build educational capacity in simulation, not only to enhance immediate learning outcomes but also to cultivate future researchers, developers, and decision-makers who can continue to apply simulation methods in meaningful ways. However, there is a growing concern within the community about the declining number of early-career researchers specialising in simulation. Without proactive investment in education and outreach, we risk a skills gap that could stifle innovation and threaten the long-term sustainability of the field. By integrating robust educational frameworks into simulation training, we can help reverse this trend and ensure that simulation research and practice continue to advance.

5.1. Added value of the C-B-A framework

This paper introduces the Customise-Build-Align (C-B-A) framework, an adaptable blueprint for aligning learning objectives, teaching activities, and assessment strategies in simulation courses. Its novelty lies in the integration, operationalisation, and contextualisation of these three key elements into a unified pedagogical structure for simulation education. To the best of our knowledge, the C-B-A framework is the first structural approach to translate constructive alignment into a domain-specific, stepwise design process explicitly tailored to teaching simulation. It provides a generic guide for designing and adapting a diverse range of simulation courses across disciplines and educational levels.

The framework was developed in response to the lack of pedagogical guidance for the design of robust simulation modelling curricula. Teaching skills-based subjects such as simulation poses challenges for educators for a number of reasons: a diverse student cohort and number, a variety of course settings, and differing educational levels at which simulation is taught. Because of this diversity, there are no standard simulation curricula readily available for instructors to adopt. We consider the framework significant for the simulation community, particularly in the context of education and training.

This framework advances the currently limited theory in simulation education, which consists primarily of individual examples of courses taught and assessed by experienced simulation educators (e.g., Altiok et al., 2001; Hoad & Kunc, 2018; Jacobson et al., 1994; Skoogh et al., 2012; Stahl et al., 2003). The C-B-A framework links established pedagogical principles of constructive alignment (Biggs, 1996), blended learning (Low et al., 2021), grading contracts (Liu et al., 2025), and learning objectives (Bloom et al., 1956) to simulation education. Furthermore, the learning objectives provided by Krathwohl (2002) have been adapted to the context of simulation courses and are supported by illustrative examples. We believe that adopting constructive alignment is beneficial, as it enables simulation educators to embed active learning into their courses, which in turn fosters deeper learning experiences.

From a practical perspective, the C-B-A framework is suitable for simulation instructors who are either new to teaching simulation or experienced educators interested in designing new courses or adapting existing ones. The framework is adaptable because it allows instructors to tailor their courses to the specific needs of their students, whether they study engineering, computer science, life sciences, business, or other disciplines. Our experiences of teaching simulation courses in the USA, the UK, and Austria highlight the importance of addressing different learning styles and ensuring a fair workload to maintain high motivation and positive affect among students. The inclusion of practical examples, case studies, and participation in simulation competitions further enhances the learning experience by providing hands-on opportunities to apply theoretical concepts.

5.2. Reflections on the C-B-A framework

From a student perspective, we present reflections grounded in systematically collected feedback, illustrating how learners experience the principles of the C-B-A framework in practice. Students repeatedly emphasised the clarity and transparency of learning expectations ("C"), noting for example that "the contents of each session were clearly communicated at the beginning" and that "the conditions for successfully completing the course were clear and understandable from the start." They also appreciated ongoing access to the intended learning outcomes through the learning platform, stating that "the learning objectives were discussed at the beginning of the course and were permanently accessible via the student portal." Feedback highlighted the structured, cohesive, and motivating learning design, aligning strongly with the experiential and active learning focus of the "B" step. Students remarked that "the lecture parts were structured, aligned, and built on each other," and that "the way the course was taught motivated me to engage with the content, and it even led directly to a topic for my master's thesis." Others described the course as "perfectly structured" and "very interactive". Students also highlighted the usefulness of transparent and supportive assessment ("A") design, noting that "the tasks were released early and included checkboxes so we could track our own learning progress" and that "the assessment criteria were clearly defined from the beginning." They also emphasised the clarity of task descriptions and the responsiveness of the instructor, stating that "the exercises were described clearly and comprehensibly, and the lecturer provided prompt support when issues arose." Together, these qualitative insights show that students not only recognise but explicitly value the alignment of learning objectives, learning experiences, and assessment strategies, which reinforce the benefits of the C-B-A framework from the learner's perspective.

We encourage simulation educators to apply our framework when designing their simulation courses. It has the potential to enhance simulation education practice, not only from a student's perspective by improving learning outcomes but also by increasing the visibility and uptake of simulation as a powerful analytical tool across disciplines. As Collins et al. (2023b) argue, improving simulation education can lead to broader adoption of simulation practices and, in turn, improve its accessibility. This becomes especially critical today, as advances in computing power and technology, as well as increasingly accessible simulation software and AI, are lowering technical barriers to entry. While these developments expand the potential of simulation to model complex real-world systems, they also require a new generation of practitioners equipped with the skills and confidence to use these tools effectively.

With the rapid growth of GenAI, we ought to consider its impact on assessment and student learning of simulation courses. GenAI has attracted significant interest in education research (Essien et al., 2024; 2025; Gonsalves, 2026; Lin et al., 2025; Liu & Zhong, 2025). Opinions vary, with some viewing AI as a powerful tool for enhancing student learning, whereas others express concerns about its potential misuse and ethical implications. Essien et al. (2024) report that GenAI text generators influence how business students engage in critical thinking, which raises important considerations for assessment design. Building on this, Essien et al. (2025) show that students' trust in and adoption of GenAI tools strongly depend on the perceived quality and credibility of the information available about these technologies. Furthermore, Lin et al. (2025) find that in STEM courses, AI use improved conceptual understanding and fostered higher performance in reflective thinking and collaborative problem-solving. Gonsalves (2026) argues that the impact of AI in postgraduate education extends beyond cognitive and metacognitive domains to affective capabilities, such as collaboration and ethical reasoning, and proposes a revised Bloom's taxonomy for use in assessment in an AI-enhanced era. Overall, evidence suggests that AI can improve student learning when effectively integrated into curriculum, pedagogy, and assessment design. For a comprehensive review of studies on the impact of AI on student learning, readers are referred to Liu and Zhong (2025).

5.3. Scope and directions for future work

Ultimately, our framework is based on our collective experience in teaching, shaped by decades of engagement with simulation education, mentorship in pedagogy, and collaboration with diverse learner cohorts. These insights have been instrumental in shaping the structure and principles of the framework. It draws from well-established concepts in the pedagogical literature, including constructive alignment, blended learning, and experiential learning, principles that have proven beneficial in many educational contexts (Eickholt, 2018; Hailikari et al., 2022). While we believe our framework offers a valuable starting point for enhancing simulation education, we acknowledge that it is a conceptual framework that needs to be further evaluated in different settings. Its value lies in offering a structured, pedagogically informed approach that can be iteratively refined and evaluated.

The field of simulation education would benefit from future research that rigorously evaluates the impact of this framework on student learning outcomes, engagement, and long-term skill development. For example, comparative studies could examine differences in learning outcomes, attainment, learner confidence, or career pathways between courses designed with and without this framework. Such analyses could draw on questionnaire-based surveys, pre- and post-course assessments, analyses of student artefacts, learning analytics, interviews, focus groups, observational studies, and longitudinal tracking data. We would particularly welcome insights from practitioners in other geographical regions. Such contributions can help identify where the proposed framework may require adaptation to align with different cultural norms, learning traditions, and educational expectations. Our framework could therefore be further developed by incorporating experiences from other countries and universities, exploring additional simulation software, and refining the associated teaching methods. By doing so, we can continue to improve simulation education and better prepare students for the complexities of modern technological and business environments. This ensures that learners acquire essential competencies in digitalisation, collaborative problem-solving, and knowledge generation; skills that are directly applicable in research and business practice. The growing role of AI in simulation education further highlights the need for pedagogical frameworks that help instructors integrate AI-assisted simulation, personalised feedback, and collaborative learning tools into future simulation curricula.

While we have introduced the framework in this study, its successful implementation requires a degree of pedagogical literacy and institutional support that may not be universally available. Educators new to simulation or unfamiliar with active learning approaches may find certain elements challenging to apply without further guidance or training. Therefore, accessible resources and additional examples are essential to support professional development and successful implementation.

6. Conclusion

This paper introduces an international simulation education framework to support educators in designing DES and ABS courses. Grounded in well-established pedagogical principles of constructive alignment, blended learning, and experiential learning, the framework offers a structured approach to creating learning environments that are both engaging and effective. These educational strategies are especially relevant today, as they align with contemporary expectations of learners who increasingly seek applied, flexible, and interactive modes of study.

The Customise-Build-Align (C-B-A) framework addresses the current lack of guidance for teaching simulation and supports the selection and integration of different pedagogical elements into a simulation course. It includes guidance on the selection of learning objectives (customisable to the aim and audience of the course), the structure (building the content based on the learning objectives) and assessment portfolios (aligning the learning activities and outcomes with assessment methods). The essential building blocks of a simulation course are outlined so that instructors can select from these components depending on the nature, level, and depth of understanding aimed to be achieved in the course.

We illustrate how the framework can be applied with examples of practical case studies from our own simulation courses taught in Austria, the UK, and the USA, which aim to deepen student understanding and modelling skills. These include skills for digitalisation, collaborative problem-solving, and the generation of new knowledge that can be directly implemented in research or business practice. We welcome future development of the framework through international collaboration, drawing on a wider range of institutional contexts, additional simulation tools, and alternative teaching methods to enhance the quality and accessibility of simulation education. We view this framework as a foundation for ongoing dialogue and innovation within the simulation education community.

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