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A System Dynamics Approach to Model the Technology and Knowledge Transfer Process

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ABSTRACT

This research develops a system dynamics model to represent the complex process of technology and knowledge transfer from academic research to product commercialization. The study aims to establish mathematical relationships between key variables within this process and link them to the Technology Readiness Level (TRL). Employing a system dynamics (SD) approach, a causal loop diagram (CLD) visualizes cause-and-effect relationships, while a stock and flow diagram (SFD) models the quantitative interactions between variables. Simulations were conducted to analyze the effects of various scenarios on TRL progression and associated activities. The SD approach effectively captures the dynamic complexity inherent in technology transfer, including feedback loops, time delays, and non-linear interactions. Simulation results indicate a 24–26-month timeframe for advancing from TRL 1 (basic research) to TRL 9 (commercialization), with a projected 7.5-year payback period. While lower product prices reduce the break-even point, they have minimal impact on TRL progression. The simulations further demonstrate how diverse scenarios and policy interventions influence TRL advancement and the outcomes of technology and knowledge transfer activities. This study's findings suggest that the developed dynamic systems model offers a valuable tool for policymakers, university administrators, and industry stakeholders to design and evaluate strategies for accelerating innovation commercialization. It provides a mechanism for assessing the impact of policy choices on both commercialization timelines and the financial performance of new products. The research uniquely integrates TRL with key technology transfer activities within a unified SD framework, offering a novel perspective on how policy decisions can influence the success of technology transfer and commercialization.

Keywords: Technology Transfer, Knowledge Transfer, System Dynamics, Technology Readiness Level (TRL), Innovation Commercialization, Simulation Modeling

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1. INTRODUCTION

There has been an increasing pressure on universities or higher education institutions (HEIs) to incorporate into their traditional functions and responsibilities (i.e., teaching and research as the first and second mission) a third mission, portrayed as "a contribution to society" (Abreu *et al.*, 2016; Urdari *et al.*, 2017) or also commonly known as "technology and knowledge transfer" (Branscomb *et al.*, 1999; Etzkowitz, 1998). The third mission is a broad term that encompasses all types of university activities outside of academic environments (Molas-Gallart and Castro-Martínez, 2007). It is arranged separately from the first two missions and is an addition to the conventional operations of institutions. By transmitting knowledge and technology to business and society at large, higher education institutions (HEIs) involved in this third mission activity are turning into engines that promote social and economic progress (Agasisti *et al.*, 2019; De Jong *et al.*, 2014; Secundo *et al.*, 2016). Consequently, as a result of the positive impact of the third mission on social and economic development (see Rubens *et al.*, 2017, for the review of the varied economic and social benefits of HEIs conducting third mission activities), research on technology and knowledge transfer has received considerable and growing attention, not only among scholars, but also among managers and entrepreneurs (e.g., Algieri *et al.*, 2013; Bozeman *et al.*, 2015; Capaldo *et al.*, 2016; Good *et al.*, 2019; Lee *et al.*, 2016; Su *et al.*, 2015; Yoon, 2017).

In the technology and knowledge transfer process, commonly, there are four stages. The initial stage, known as basic research, is vital to a product's market success. This initial stage focuses on fundamental scientific inquiries and exploratory studies aimed at generating new knowledge (Bozeman *et al.*, 2015). The solution from the first step will be moved to the second stage, which is technological development. In this phase, research findings are translated into tangible prototypes or technologies. This stage often involves iterative testing, refining, and validation of concepts, where early-stage innovations begin to take shape (Rubens *et al.*, 2017). In the technology commercialization stage, as technology reaches a certain level of maturity, efforts shift towards bringing it to the market. This includes preparing for production, addressing regulatory requirements, and developing marketing strategies. The final stage (i.e., market industry) involves the actual launch and commercialization of the product. Here, the focus is on market penetration, customer acquisition, and competition with existing products (Etzkowitz, 1998). Successful transition through the previous stages significantly impacts a product's ability to capture market share and generate revenue.

Pujotomo *et al.* (2023) attempted to link between these stages with the technology readiness level (TRL). It is a type of measurement system used to assess the maturity level of a particular technology (Mankins, 1995). TRLs range from 1 (basic principles observed) to 9 (actual system proven in operational environment). Understanding the TRL allows stakeholders to gauge the technology's readiness for market entry and investment, guiding decisions on resource allocation and development efforts.

Activities in the technology and knowledge transfer process are considered as dynamic processes that happen in a highly complex environment. They involve numerous interactions within HEI and with the external environment (e.g., industries). Time lag may also occur between actions and results, adding complexity to the processes, especially regarding consequences of one policy.

Despite the growing emphasis on technology and knowledge transfer, existing models often fall short in capturing the complexities involved. Most studies have focused on individual aspects of the transfer process, neglecting nonlinear interactions, feedback loops, and time delays characteristic of real-world scenarios. As a result, there is a lack of comprehensive dynamic models that in particular, link TRL with activities in the technology and knowledge transfer process.

While previous research has investigated various elements of technology and knowledge transfer, there remains a significant gap in modeling that integrates TRL and activities in technology and knowledge transfer within a unified framework. Many existing studies utilize static models or overlook the dynamic interactions inherent in the transfer process. This study addresses this gap by developing a system dynamics (SD) model that simulates the interactions between TRL development and investment dynamics, providing insights into how different policies can affect commercialization outcomes.

The features of SD are dynamics, tightly coupled, feedback-oriented, nonlinear, self-organizing, adaptive, history-dependent, policy resistant, counterintuitive, and characterized by trade-offs (Xia *et al.*, 2018). Given that activities in the technology and knowledge transfer process exhibit a large number of the abovementioned features, this study then aims to provide an SD perspective of activities in these two stages that can be used to capture the essence of this dynamic complexity. We construct an SD model that offers a theoretical explanation of the inherent critical dynamic complexities regarding activities in the technology and knowledge transfer process. Our suggested framework provides insights that may be implemented by academics and entrepreneurs to enhance the effective transfer of technical discoveries from academic research to the commercial market.

The following research questions are posed:

1. How can the SD framework be used to model the technology and knowledge transfer process from research to commercialization?
2. How do changes in variables such as resource allocation and product pricing affect the develop-

ment of TRL and activities in the technology and knowledge transfer process?
3. What insights can be gained from modeling policy scenarios to accelerate the commercialization of academic research?

Our study offers the following contributions to literature. First, we propose a comprehensive framework that integrates activities in the technology and knowledge transfer process into the SD framework. Previous related research (see Section 2) did not embrace these activities into their SD model. Second, we link TRL and activities in the technology and knowledge transfer process into the SD model. Finally, we do a simulation to give an illustration of how SD can be used to model different policies and their outputs.

The remainder of this paper is structured as follows. In the next section, a literature review is presented. Section 3 shows the model development in the SD framework, including causal loop diagram (CLD) and stock and flow diagram (SFD). Section 4 presents the simulation result; and finally, the last section concludes.

2. LITERATURE REVIEW

To see previous and related research in this research area, especially that employed the SD framework, we look for articles in the Scopus database (https://www.scopus.com/), following Mongeon and Paul-Hus (2016), who mentioned, "Scopus includes most of the journals indexed in WoS [Web of Science]." We use this search query: TITLE-ABS-KEY (("system dynamic*") AND (universit* OR education) AND ("technology transfer" OR "knowledge transfer" OR "technology licensing")) AND (LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (DOCTYPE, "ar"))[1]. Therefore, articles whose title, abstract, or keywords contain the search query would be extracted. For quality assurance, document types are limited to peer-reviewed articles published in journals, as these sources are the most beneficial for literature reviews (Saunders *et al.*, 2012). From a pragmatic viewpoint, only English-language articles are included.

The search yields only 8 articles. This low yield might indicate that this research area is under-studied. From those 8 articles, we only discuss 5 articles since the article from Zhai (2013), Wu and Shang (2019), and Krivtsov *et al.* (2023) are considered as not relevant. Zhai (2013) used the knowledge transfer theory to establish a system dynamics model of knowledge transfer in engineering education without involving the technology transfer office; Wu and Shang (2019) discussed the tacit knowledge transfer process in massive open online courses; Krivtsov *et al.* (2023) presented a concise hands-on course on SD modelling and systems thinking and discuss its potential developments.

To explore the state of research related to the technology and knowledge transfer process, particularly employing SD frameworks, we examined key studies in this domain. The existing literature reveals several important contributions while highlighting critical gaps that this study aims to address.

Aparicio *et al.* (2016) highlights the role of innovative entrepreneurship in driving economic growth using an SD approach. Their model effectively captures feedback mechanisms and policy implications but limits its focus to macroeconomic outcomes without addressing the micro-level complexities of technology transfer. Similarly, Hamilton (2017) emphasizes the importance of resource management in university technology transfer, particularly in the context of historically black colleges and universities (HBCUs). While the study introduces a robust budgeting tool, it neglects broader institutional and relational dynamics, such as collaboration and alignment among stakeholders, which are vital for effective technology transfer.

Xiao *et al.* (2018) provided valuable insights into knowledge transfer efficiency within university-industry collaborations using a social network theory framework. However, their study overlooks the dynamic interactions and feedback loops inherent in the technology transfer process. Wu *et al.* (2022) focus on synergistic innovation between industry and academia, emphasizing information flow and trust relationships. Although they shed light on critical factors like organizational distance and collaboration, their findings are primarily static and do not account for evolving conditions in real-world scenarios.

Dolmans *et al.* (2023) offer an in-depth exploration of boundary-spanning abilities developed during academic engagement with industry. While their qualitative findings enrich our understanding of the interpersonal and cognitive aspects of knowledge transfer, the absence of quantitative modeling leaves a gap in understanding how these skills impact measurable outcomes in technology transfer.

Collectively, these studies underscore the multifaceted nature of technology and knowledge transfer, revealing both the challenges and opportunities inherent in this process. While methodologies such as SD, social network analysis, and qualitative approaches provide valuable frameworks for understanding technology transfer, the absence of integrated models that capture the dynamic interactions and feedback loops remains a critical gap in the literature. This synthesis highlights the need for research that combines both qualitative and quantitative methods to develop a holistic understanding of technology and knowledge transfer processes. Specifically, integrating the insights from these studies into a comprehen-

[1] The asterisk (*) is the wildcard and will search for any word that starts with what we have before it.

sive model that links TRL and activities in the technology and knowledge transfer processes could significantly enhance the understanding of how various factors impact technology commercialization. Such an approach would not only contribute to academic discourse but also provide practical guidance for policymakers and stakeholders in optimizing technology transfer strategies.

Despite the valuable insights offered by these studies, significant gaps remain. Many existing models focus on specific aspects of the technology transfer process, often adopting static approaches that fail to capture the dynamic complexity of real-world scenarios. For instance, most studies do not integrate the concept of TRL with the dynamic feedback mechanisms, nonlinear interactions, and time delays that characterize the technology transfer journey. Moreover, limited attention has been paid to the interplay between resource allocation, policy decisions, and their impacts on TRL advancement. While financial resource planning (Hamilton, 2017) and market conditions (Wu *et al.*, 2022) have been explored, the interdependencies between these factors and their cumulative effects on technology commercialization have not been fully addressed.

This present study then seeks to address these limitations by employing a system dynamics framework to integrate TRL with the activities involved in technology and knowledge transfer. Unlike previous research, this approach captures the dynamic interactions among stakeholders, resources, and processes over time. By doing so, it provides a more holistic understanding of the challenges and opportunities in advancing technology from research to market. Furthermore, this research adds value by exploring how policy scenarios and strategic investments influence the commercialization timeline and outcomes. By simulating different allocation strategies and market conditions, we aim to offer actionable insights for stakeholders in academia, industry, and policymaking.

3. METHODOLOGY

This research employs a system dynamics (SD) approach, which is particularly suited for capturing the complex interactions and feedback loops inherent in the technology transfer process. SD was pioneered by Forrester (1958) and later expanded by Sterman (2000), offering a robust framework for analyzing systems characterized by nonlinear interactions, time delays, and feedback mechanisms. The choice of SD aligns with the study's objective to model the technology readiness level (TRL) progression and its dynamic relationship with activities in technology and knowledge transfer.

SD was first created by Forrester (1958) to use computer simulations to study complicated behaviors in the social sciences, particularly in management. Before the SD, decisions made about how to approach an issue frequently had unanticipated consequences; for this reason, creating a new methodology was urgently needed. Rather than the system's variables, the structure in which they are impacting one another is blamed for the system's counterintuitive behavior (Sterman, 2000). SD has been modelled to assist the decision-making process in the field of supply chain management (e.g., Alamerew and Brissaud, 2020; Rebs *et al.*, 2019), waste management (e.g., Ardiyawan and Ulkhaq, 2024; Liu *et al.*, 2020; Pinha and Sagawa, 2020), and agriculture (e.g., Turner *et al.*, 2016; Walters *et al.*, 2016).

The first step in the SD modeling process is to clearly define the problem and objective, as well as understand the system boundaries (Sterman, 2000). This study focuses on two primary challenges: delays in achieving higher TRLs and resource allocation issues in the technology transfer process. The delays often stem from technical challenges, resource constraints, regulatory hurdles, and misaligned stakeholder objectives (Bozeman *et al.*, 2015; Aparicio *et al.*, 2015). Resource allocation issues, such as valuation uncertainty and lack of investor confidence, further complicate the process (Xiao *et al.*, 2018; Wu *et al.*, 2022). Addressing these challenges requires a dynamic modeling approach that captures interdependencies and provides actionable insights.

The second step involves constructing a causal loop diagram (CLD) to visualize the feedback mechanisms and cause-and-effect relationships within the technology transfer process. CLDs are commonly used in SD to illustrate the structure of complex systems (Sterman, 2000; Xia *et al.*, 2018). This study's CLD links critical variables, such as research activities, product development, resource allocation, and market dynamics, highlighting both reinforcing and balancing feedback loops. For instance, a balancing loop represents the relationship between product development and quality improvement, where resource constraints and delays impact the speed of quality enhancement (Pinha and Sagawa, 2020; Hamilton, 2017).

The next step is to develop a stock and flow diagram (SFD) to quantify the relationships identified in the CLD. SFDs represent accumulations (stocks) and flows over time, enabling a detailed analysis of how changes in one variable affect the entire system (Sterman, 2000; Bala *et al.*, 2018). In this study, the SFD integrates the TRL framework (Mankins, 1995) to model the progression of technology from basic research (TRL 1) to commercialization (TRL 9). Key variables such as time delays, resource availability, and quality gaps are incorporated to simulate realistic conditions.

The final step involves conducting simulations to test various policy and investment scenarios. This step leverages the dynamic model to analyze how changes in resource allocation, product pricing, and stakeholder coordination impact TRL advancement and commercialization outcomes. For example, the study examines the impact of reduced funding on the time required to reach TRL milestones, following similar approaches in prior SD applications (Rebs *et al.*, 2019; Ardiyawan and Ulkhaq, 2024). The results provide insights into strategies for minimizing delays and optimizing investment flows.

In the following subsections, we discuss each step in the SD modelling process which we consider in this study. Notice that the simulation result will be provided in the next section.

3.1 Define the Problem and Objective

The first step in the SD modeling process is to clearly define the problem and objective as well as understand the boundaries of the system we are working with. In this study, we focus on two significant challenges: the delays in reaching TRL and the issues surrounding investment in the technology and knowledge transfer processes.

The delays in reaching TRL can stem from a variety of factors that considerably slow down the entire technology transfer journey. One key factor is technical challenges. Each TRL comes with its own set of technical requirements that need to be met before moving on to the next level. For example, transitioning from TRL 4, which involves validating components in a lab setting, to TRL 5, where we validate the entire system in a relevant environment, often requires extensive testing and multiple iterations to prove that the technology is reliable and effective. Unforeseen engineering problems, limitations in materials, or design flaws can easily lead to delays during this phase (Bozeman *et al.*, 2015).

Another important factor is resource constraints. Advancing through TRLs demands substantial investments in research and development (R&D), which includes funding, skilled personnel, and necessary facilities. When access to financial resources is limited, it can really slow down progress. For instance, if a project doesn't have enough funding for prototyping and testing, it might take longer to reach the necessary validations needed to move up to the next TRL (Aparicio *et al.*, 2016).

We also need to consider regulatory and compliance issues. Adhering to industry regulations and standards can introduce significant delays, particularly in sectors like healthcare and energy, where rigorous testing and certification are essential. Navigating these complex regulatory frameworks can be a time-consuming process, often causing progress through the TRLs to stall (Hamilton, 2017).

Lastly, there is the aspect of coordination among stakeholders. Effective technology transfer usually involves collaboration among a variety of stakeholders, including researchers, industry partners, and government agencies. When these parties have misaligned goals, face communication barriers, or have different timelines, it can create bottlenecks that further delay advancement through the TRLs (Dolmans *et al.*, 2023).

Next, we also highlight the investment challenges in technology and knowledge transfer process. Investment is crucial for successfully bringing new technologies to market; however, several challenges can complicate the process of securing that investment during technology transfer. One major hurdle is valuation uncertainty. Early-stage technologies often struggle to establish their market value, facing ambiguity regarding their performance, market demand, and the competitive landscape. This uncertainty can lead investors to hesitate, fearing they may take on high risks with uncertain returns (Xiao *et al.*, 2018). Additionally, there are high initial costs associated with developing technology and progressing through various Technology Readiness Levels (TRLs). Many innovative technologies require significant capital for research and development (R&D), prototyping, and regulatory compliance. For startups and academic institutions, finding sufficient funding to cover these expenses can be particularly challenging, especially when they lack extensive financial backing (Wu *et al.*, 2022).

Another issue is the lack of investor confidence; investors may be wary of committing funds to technologies that do not have a clear path to market or established performance metrics. This skepticism often stems from past failures of similar projects or doubts about the expertise of the team behind the technology (Dolmans *et al.*, 2023). Furthermore, misalignment of interests among stakeholders can create additional complications. Researchers, entrepreneurs, and investors may prioritize different objectives—while researchers focus on scientific discovery and exploration, investors typically seek quicker returns. This disconnect can lead to conflicts that hinder investment decisions and resource allocation (Hamilton, 2017). Finally, overall market readiness can significantly influence investment decisions. If technology is entering a market perceived as saturated or faces established competitors with similar products, investors might be less inclined to take a chance on something new. Understanding these market dynamics is essential for attracting the necessary investment (Aparicio *et al.*, 2016).

Delays in reaching TRL and investment issues are interconnected challenges in the technology and knowledge transfer process. Addressing these challenges requires a comprehensive understanding of the complexities involved, along with strategic planning and effective stakeholder collaboration. By leveraging SD modeling, researchers can simulate various scenarios to identify effective strategies for minimizing delays and optimizing investment flows, thereby facilitating a more efficient technology and knowledge transfer process (Bozeman *et al.*, 2015; Mankins, 1995).

3.2 Create a Causal Loop Diagram

Next, a causal loop diagram (CLD) is created, in

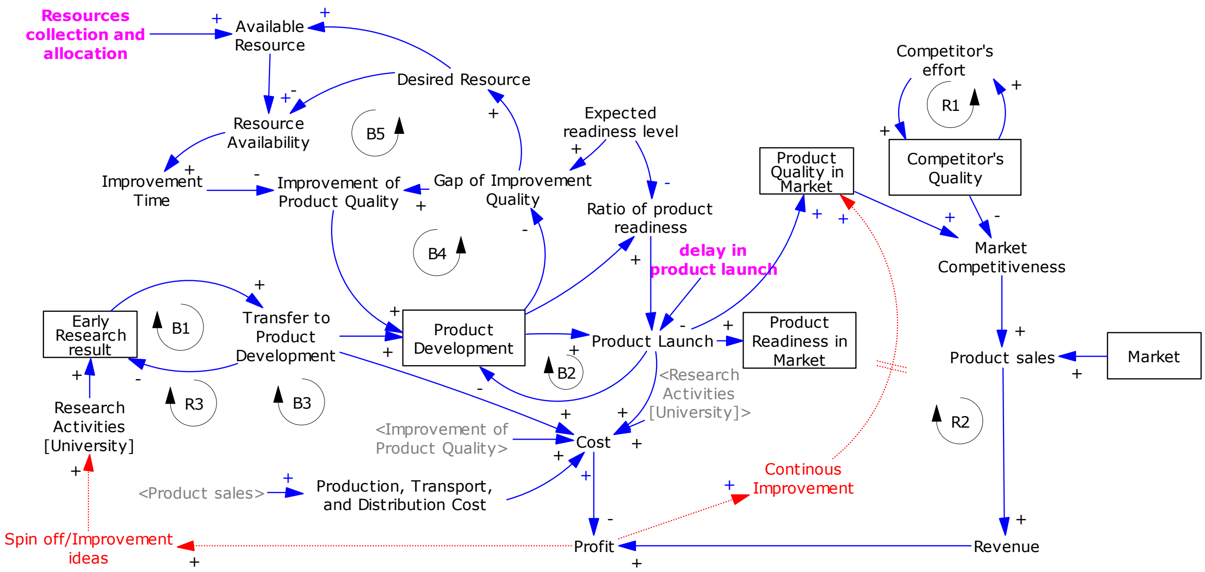


Figure 1. The causal loop diagram.

which the main variables are connected in a feedback-based way. The feedback mechanisms that are formed inside complex systems, along with the intersections, dynamics, and delays connected to the variables that cause them, are better understood and illustrated by CLD. By illustrating these dynamics, CLD helps identify key variables and their interconnections, laying the groundwork for deeper analysis. For the given situation, CLD provides a useful method for comprehending and expressing the interconnected components of the systems as well as the cause-and-effect relationships. CLD links system variables by arrows. These arrows show the direction of influence while the polarity accompanying arrows depicts the effect of influence: positive for direct and negative for an inverse influence.

The CLD describing activities in the technology and knowledge transfer process is shown in Figure 1. Note that CLD is used to represent the feedback mechanisms and cause-and-effect relationships within the technology and knowledge transfer process (Sterman, 2000). Notice that arcs describe the directions of influence. A positive arc can be read as “an increase in variable A leads to an increase in variable B”. conversely, a negative arc can be read as “an increase in variable A leads to a decrease in variable B”. When arrows link one variable to another through a sequence of other variables, it creates a feedback loop. With CLD, feedback loops may be expressed in two main types: balancing loops (represented by letter “B”) and reinforcing loops (“R”). Balancing loops occur when there is an attempt to solve a problem or attain a goal. They are also known as neutralizing loops, where cause and effect cycles aim to counteract a change by pushing in the opposite direction. On the other hand, reinforcing loops represents a growing action where each action adds to another and may be referred to as virtuous cycles when they produce desirable effects or vicious cycles when they produce negative effects.

In this study’s CLD, The system starts with *research activities*[2] conducting by the university (see the bottom left in Figure 1) and accumulated in early research result. After certain value of accumulation in early research result level, then, the results will be transferred to the so-called *product development* process, in which *product development* level represents the accumulation of process result. These variables form negative feedback (balancing loop, indicated as “B1”) since *transfer to product development* will reduce the value of early research result—meaning that the early research result then moves to the next stage of development, which is *product development*.

The *product development* level will be increased through such efforts to improve product quality. In this sense, there will be another balancing loop (B4) which involves *product development*, *gap of improvement quality*, and *improvement of product quality*. It is negative feedback, as it is intended to close the gap between *product development* level and expected quality (represented by *gap of quality improvement* in the CLD).

B5 represents the process to close the gap, which involves *gap of improvement quality*, *desired resources*, *resources availability*, *improvement time*, *improvement of product quality*, and *product development*. In this loop, closing the gap requires certain number of resources (it could be money, human resources, expertise, facility, etc.) represented by *desired resources*. The fulfilment of this *desired resources* depends on the resources allocation policy based on how many resources available on the institution (or university) or their efforts to collect the available resources (it is represented by *available re-*

[2] Variables in the CLD are represented by italic.

Table 1. Reinforcing loops and balancing loops in the causal loop diagram

Loops	Related Variables
R1	*Competitor's quality → Competitor's effort → Competitor's quality*
R2	*Product quality in market → Market competitiveness → Product sales → Revenue → Profit → Continuous improvement → Product quality in market*
R3	*Early research results → Transfer to product development → Product development → Product launch → Product quality in market → Market competitiveness → Product sales → Revenue → Profit → Spin-off/improvement ideas → Research activities [university] → Early research results*
B1	*Early research results → Transfer to product development → Early research results*
B2	*Product development → Product launch → Product development*
B3	*Early research results → Transfer to product development → Cost → Profit → Spin-off/improvement ideas → Research activities [university] → Early research results*
B4	*Product development → Gap of improvement quality → Improvement of product quality → Product development*
B5	*Product development → Gap of improvement quality → Desired resources → Resources availability → Improvement time → Improvement of product quality → Product development*

sources). Therefore, resources availability is the ratio between available resources and the desired resources which might affect improvement time and improvement of product quality. It means the less resources availability will affect in longer improvement time and affect the more delay in product development achievement to meet expected quality.

Once product development met with expected readiness level (which is represented by *ratio of product quality* in the CLD), then *product launch* might happen. However, this event (i.e., the *product launch*) might be affected by a delay in product launch. Similar to B1, the *product development* level will move to *product launch* and form B2.

When the product is launched to the market, the product will bring specific quality and can be compared with similar product in the market (from competitors), represented by *product quality in market* in this CLD. The quality might be better or worse than the competitors. This condition will affect *market competitiveness* and determine *product sales*, *revenue*, as well as *profit*. This condition might be tightly related to *continuous improvement* to increase *product quality in market*—and forming R^2. From the competitor's perspective, the competitor also constantly makes improvement (*competitor's effort*), so that it will form R1.

The profit gained from sales might go to the continuous improvement process, or to develop a spin-off (represented by *spin-off/improvement ideas*). This will form B3 and R3, as well as lead to similar CLD but with the different product. All loops in the CLD are summarized in Table 1.

3.3 Establish Stock and Flow Diagram

CLD captures causal relationships, and it is useful for understanding the structure of the model. However, CLD cannot show the mathematical relationships between variables in the model. A stock and flow diagram (SFD) is then developed to show the model including the relationships between variables. To develop a quantitative SFD from qualitative CLD, four building blocks are used: stock, flow, valve, and cloud (see Table 2).

In developing SFD, this research also attempts to link between activities in the technology development and commercialization stages as captured in the CLD and the TRL number. We employ NASA's TRL concept as it is widely used in the literature of technology commercialization. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest.[3] The SFD of this research is shown in Figure 2.

[3] When a technology is at TRL 1, scientific research is beginning, and those results are being translated into future research and development. TRL 2 occurs once the basic principles have been studied, and practical applications can be applied to those initial findings. TRL 2 technology is very speculative, as there is little to no experimental proof of concept for the technology. When active research and design begin, a technology is elevated to TRL 3. Generally, both analytical and laboratory studies are required at this level to see if a technology is viable and ready to proceed further through the development process. Often during TRL 3, a proof-of-concept (PoC) model is constructed. Once the PoC technology is ready, the technology advances to TRL 4. During TRL 4, multiple component pieces are tested with one another. TRL 5 is a continuation of TRL 4, however, a technology that is at 5 is identified as a breadboard technology and must undergo more rigorous testing than technology that is only at TRL 4. Simulations should be run in environments that are as close to realistic as possible. Once the testing of TRL 5 is complete, a technology may advance to TRL 6. A TRL 6 technology has a fully functional prototype or representational model. TRL 7 technology requires that the working model or prototype be demonstrated in a space environment. TRL 8 technology has been tested and "flight qualified" and it's ready for implementation into an already existing technology or technology system. Once a technology has been "flight proven" during a successful mission, it can be called TRL 9.

Table 2. Components of stock and flow diagram

Building Block	Symbol	Description
Stock		It accumulates or integrates the state of systems based on time
Flow		It changes the value of the stock
Valve		It controls the amount of inflow and outflow, and shows a boundary point of entry and exit of cloud
Cloud		A point of entry or exit

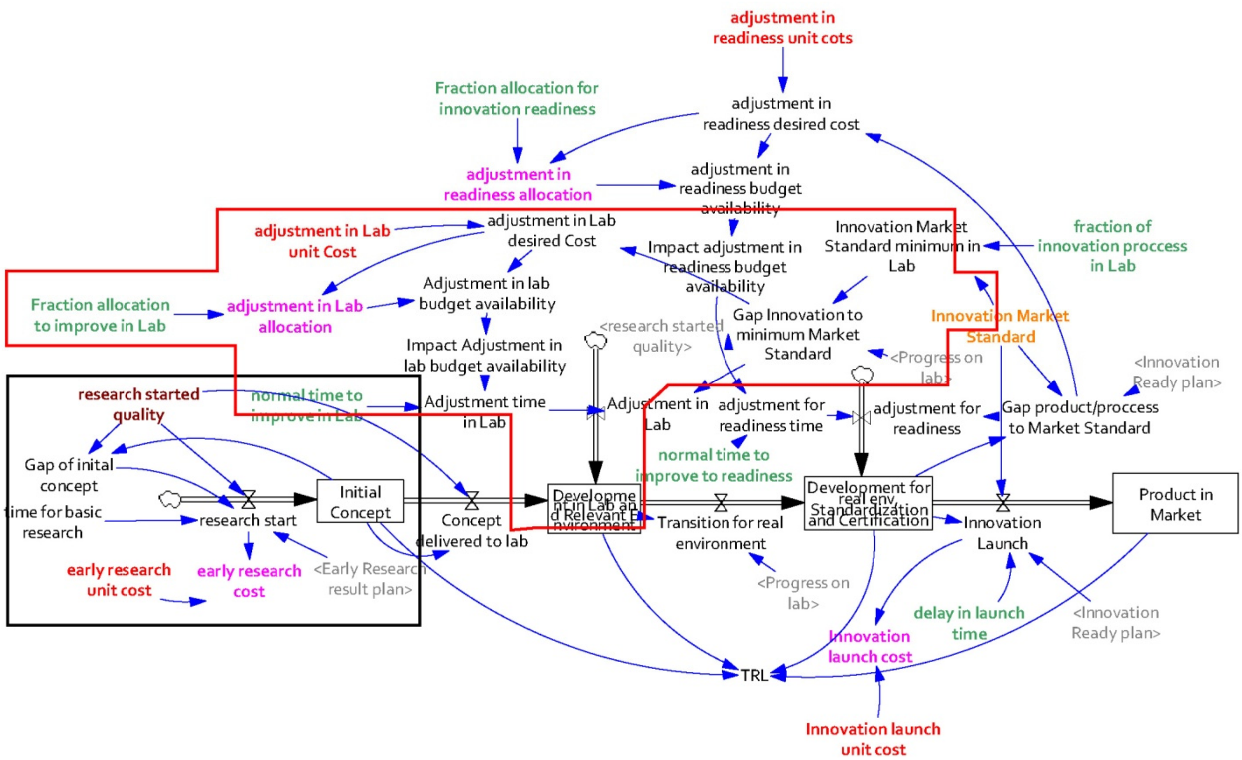


Figure 2. The stock and flow diagram

This system begins with *research start* (as a “flow” and represents TRL 1) and it will be accumulated as *initial concept* (as a “stock”). The *research start* is influenced by *gap of initial concept*, *time for basic research*, and the quality of the initial research (represented by *research started quality* variable). Once the *initial concept* is met (representing TRL 2), the concept will be delivered in a laboratory or simply “lab” (represented by *concept delivered to lab*). In this laboratory environment, some endeavors must be made to improve the concept until it reaches TRL 5 (represented by the “stock” *development in lab and relevant environment*). The improvement process is influenced by the gap between the concept and the actual condition as well as fund allocation (represented by *innovation market standard minimum in lab*). This “gap” needs to be reduced. Consequently, the gap depends on the required fund as well as processing time. Therefore, if the funds are not available, the processing time could be longer. The fund represents not only money, but all the resources needed, including human resources, expertise, productivity, access to technology, materials, and facilities. This TRL development can be simply illustrated in Figure 3.

TRL 6 starts when a model or prototype has been tested in the relevant environment. Again, the improvement process will be made to increase the value of TRL to reach TRL 9 (represented by the “stock” *Development for real env, standardization and certification*). This stock is influenced by *adjustment in lab desired cost* (or the required resources); and by *adjustment in lab desired cost* is influenced by *adjustment in lab unit cost* (this determines how many costs allocated on the *adjustment in lab allocation*). After TRL 9 is reached, it will trigger the *innovation launch* as a product enters the market (represented by the

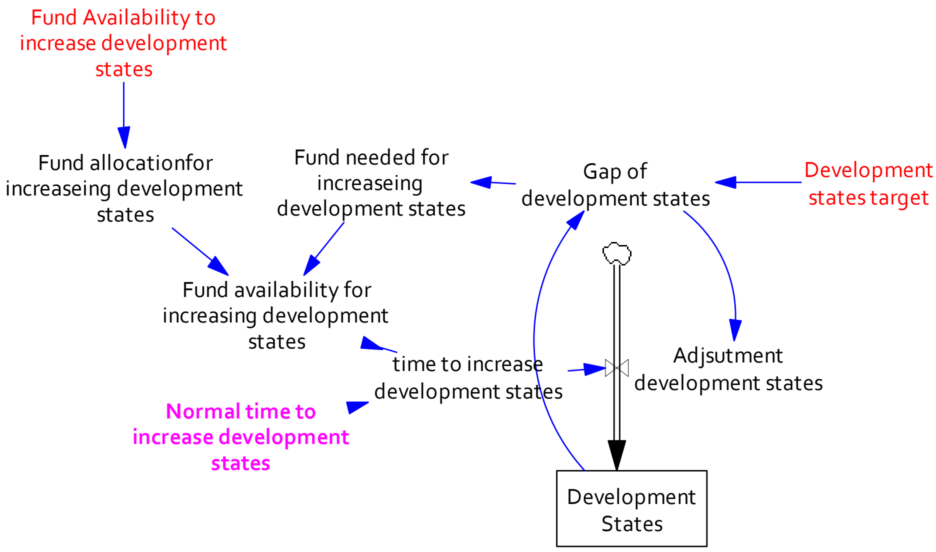


Figure 3. The development of TRL number.

"stock" *product in market*). Mathematical formulations can be described as follows:

Gap of initial concept = Research started quality – Initial concept (1)

Research start = IF THEN ELSE (*Early research result plan >= Research started quality*, 0, *Gap of initial concept/Time for basic research*) (2)

Concept delivered to lab = IF THEN ELSE (*Early Research result plan < Research started quality*, 0, *Initial concept/Delivery time)* (3)

Development in lab and relevant environment = Concept delivered to lab + Transition for real environment (4)

Transition for real environment = IF THEN ELSE (*Progress on lab < Innovation market standard minimum in lab*, 0, *Development in lab and relevant environment/delivery time*) with TRL/month unit (5)

Gap innovation to minimum market standard = IF THEN ELSE (*Progress on lab < Research started quality*, 0, MAX (0, *Innovation market standard minimum in lab - Progress on lab*)) (6)

Adjustment in lab desired cost = Adjustment in lab unit cost × Gap innovation to minimum market standard (7)

Adjustment in lab allocation = Adjustment in lab desired cost × Proportion allocation to improve in lab (8)

Adjustment in lab budget availability = Adjustment in lab allocation/ Adjustment in lab desired cost (9)

Adjustment time in lab = Impact allocation in lab to delay × normal time to improve in lab (10)

Adjustment in lab = Gap innovation to minimum market standard/ Adjustment time in lab (11)

Innovation launch = IF THEN ELSE (*Innovation ready plan < Innovation market standard*, 0, *Development for real env, standardization and certification/Delay in launch time*) (12)

After the product is launched onto the market, the quality of the product is then compared to the competitors' products available in the market. Figure 4 illustrates market dynamics and competition after the product is launched. There are two main structures of market competition: potential market and captive market. The first is a market that initially does not consume the product; while the latter is a market that currently consumes the product. The dynamics of the potential market is determined by the new market (represented by *change in the potential market*), transition from the potential market to the captive market, and *market losses* from captive market to the potential market. The flow from the potential market to the captive market is represented by *competitiveness ratio* which means the ratio of product quality to the competitor's product quality. With this structure, the

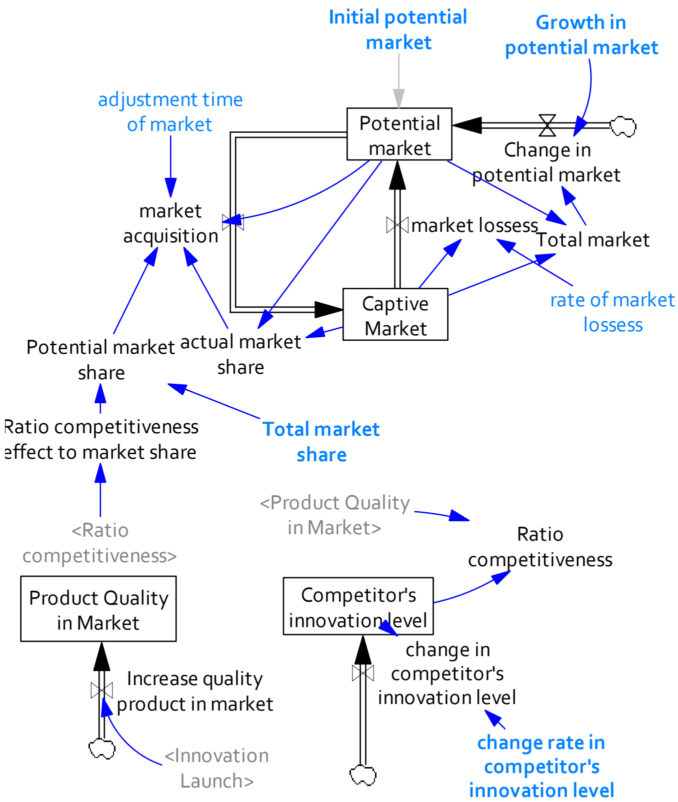


Figure 4. Market dynamics and competition sub-model.

speed of innovation (especially continuous improvement) is considered essential. If the improvement is slower than the improvement of the competitor, then the market share will be decreased, and the captive market will be reduced. Therefore, even after the product is launched, the improvement still matters to determine how long the product will survive in the market and, accordingly, will determine the cash flow. Mathematical formulations of this market dynamic can be described as follows:

Product quality in market$_t$ = *Product quality in market*$_{t-1}$ + *Increase quality product in market* (13)

Increase quality product in market = *Innovation Launch*/3[4] (14)

Competitor's innovation level = *Competitor's innovation level*$_{t-1}$ + *Change in competitor's innovation level* (15)

Change in competitor's innovation level = *Competitor's innovation level* x *Change rate in competitor's innovation level* (16)

Ratio competitiveness = *Product quality in market/Competitor's innovation level* (17)

Potential market = *Potential market*$_{t-1}$ + *Change in potential market* – *Market acquisition* + *Market losses,* where initial *Potential market* is assumed to be 10000 customers (18)

Captive market = *Captive Market*$_{t-1}$ + *Market acquisition* – *Market losses,* where initial *Captive market* is assumed to be 0 customer (19)

Change in potential market = *Potential market* x *Growth in potential market* (20)

Market acquisition = MAX (0, *Potential market share* – *Actual market share)* x *Potential market/Adjustment time of market* (21)

Market losses = *Captive market* x *Rate of market losses* (22)

Potential market share = *Total market share* x *Ratio competitiveness effect to market share* (23)

Actual market share = *Captive market/Potential market* (24)

[4] It is assumed that product quality has a value level of 3 (out of 5). Later on in the simulation, it can be changed easily.

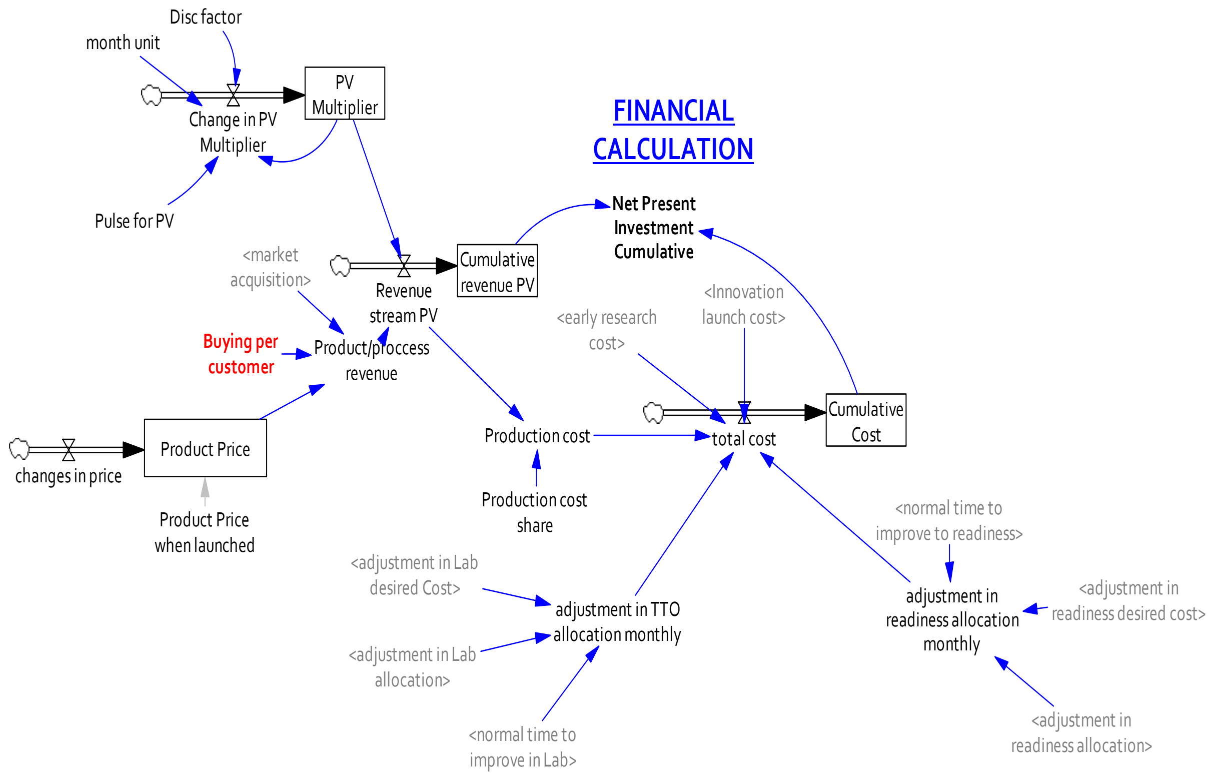


Figure 5. Financial dynamics sub-model.

Finally, we also model the financial dynamics as illustrated in Figure 5. The revenue is determined by *product price* and *changes in price*, *buying per customer*, *number of market acquisition* (i.e., customer who decides to buy the product), and adjusted by present value (*PV*) *multiplier* to convert it into the present value. The revenue streams each month will be accumulated as *cumulative revenue PV*. On the cost side, the cost consists of the cost needed in the TRL development process (i.e., cost of initial concept, development in lab and relevant environment, development for real environment, standardization and certification, as well as product in market) and production cost. This total cost will be accumulated as *cumulative cost*. The aggregate of *cumulative revenue PV* and *cumulative cost* represents *cumulative new product investment curve* (NPIC). Mathematical formulations of these financial dynamics can be described as follows:

Product/process revenue = *Market acquisition* x *Product price* x *Buying per customer* (25)

Product price = *Product price*$_{t-1}$ + *Changes in price* (26)

Revenue stream PV = *Product/process revenue* x *PV multiplier* (27)

' multiplier = *PV Multiplier*$_t$ – (*PV multiplier*$_{t-1}$ x *Disc factor/month unit* x *Pulse for PV* (28)

Cumulative revenue PV = *Cumulative revenue PV*$_{t-1}$ + *Revenue stream PV* (29)

Total cost = (*Adjustment in readiness allocation monthly* + *Adjustment in TTO allocation monthly* + *Adjustment in TTO allocation monthly* + *Early research cost* + *Innovation launch cost*) + *Production cost* (30)

Adjustment in lab allocation monthly = MIN (*Adjustment in lab allocation, Adjustment in lab desired cost)/Normal time to improve in lab* (31)

Adjustment in readiness allocation monthly = MIN (*Adjustment in readiness allocation, Adjustment in readiness desired cost)/Normal time to improve to readiness* (32)

Innovation launch cost = *Innovation launch* x *Innovation launch unit cost* (33)

Early research cost = *Research start* x *Early research unit cost* (34)

Production cost = *Revenue stream PV* x *Production cost share* (35)

4. SIMULATION: RESULTS AND DISCUSSION

4.1 Model set up

Model set up is related to parameterization of model's variables as well as time and time step set up for simulation. Model parameterization is shown in Table 3. Notice that some assumptions are made (see Value or Initial Value columns of Table 3). In the simulation, these constants can be changed easily to depending on the condition.

Table 3. Model parameterization

No	Variables	Brief Description	Value or Initial Value	Unit	Variable Type
		Main Model (see Figure 2)			
1	Initial concept	From TRL 1 to TRL 2	0	quality	level
2	Early research unit cost	Cost needed to increase TRL from TRL 1 to TRL 2	1,000	$/quality	constant
3	Development in lab and relevant environment	From TRL 3 to TRL 5	0	quality	level
4	Development for real env, standardization and certification	From TRL 6 to TRL 9	0	quality	level
5	Product readiness in market	TRL 9	0	quality	level
6	Research started quality	Target of early research (i.e., TRL 2)	2	quality	constant
7	Adjustment in lab unit cost	Cost needed to increase TRL from TRL 3 to TRL 5	500	$/quality	constant
8	(Proportion) allocation to improve in lab	Proportion on how many cost needed will be fulfilled to develop from TRL 3 to TRL 5	1		constant
9	Normal time to improve in Lab	Time needed to increase *Development in lab and relevant environment* level to achieve the target (i.e., TRL 5) if fund needed is fulfilled	6	month	constant
10	Adjustment in readiness unit cots	Cost needed to increase TRL from TRL 6 to TRL 9	250	$/quality	constant
11	(Proportion) allocation for innovation readiness	Proportion on how many cost needed will be fulfilled on TRL 6-9	1		constant
12	Normal time to improve to readiness	Time needed to increase *Development for real env, standardization and certification* level to achieve the target (i.e., TRL 9) if fund needed is fulfilled	12	month	constant
13	Innovation market standard	Target (i.e., TRL 9)	9	quality	constant
14	Delay in launch time	Delay to launch the product once the product reaches TRL 9	3	month	constant
15	Innovation launch unit cost	Launching and marketing cost	12,000	$/quality	constant
		Market dynamics sub-model (see Figure 4)			
16	Potential market	Number of potential markets	10,000	customer	level
17	Captive market	Number of customers that consumes the product	0	customer	level
18	Product quality in market	Quality of product	3	quality	level
19	Change rate in competitor's innovation level	Change rate of competitor's quality	0	1/month	constant
20	Competitor's innovation level	Quality of competitor's product	3	quality	level

Table 3. Model parameterization (Continued)

No	Variables	Brief Description	Value or Initial Value	Unit	Variable Type
20	Competitor's innovation level	Quality of competitor's product	3	quality	level
21	Growth in potential market	Growth of potential market each month	0.004166667	1/month	Constant
22	Rate of market lossess	Rate of market lossess represented by customers who stop consuming the product	0.0005	1/month	constant
23	Adjustment time of market	Time needed to achieve market share target	6	month	constant
		Financial dynamics sub-model (see Figure 5)			
24	Cumulative revenue PV	Cumulative revenue starts when product is launched and adjusted to present value	0	$	level
25	Product price	Product price	35	$/unit	level
26	Cumulative cost	It consists of cost of development process and cost of production phase	0	$	level
27	PV multiplier	It is used to adjust revenue driven by discount factor	1		level
28	Disc factor	Discount factor to adjust revenue per annum	6%	per annum	constant
29	Buying per customer	Number of products bought by a customer	2	unit/customer	constant
30	Production cost share	Production cost share from product price	40%		constant
31	Net present investment cumulative	The difference between cumulative revenue and cumulative cost to track the valey of death performance	Cumulative revenue PV – Cumulative Cost		auxilary

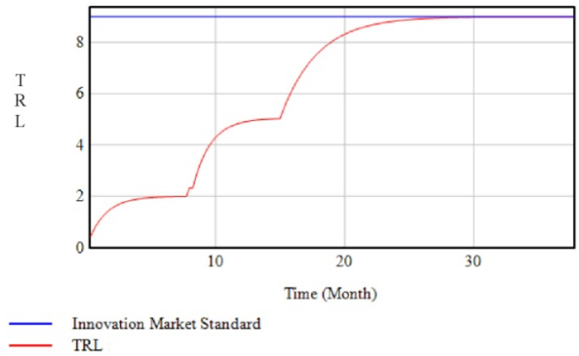
4.2 Results

First, we run a simulation to show how long time needed to reach TRL 9 (when the product is launched to the market) from TRL 1 (early research). Time needed (by using previous assumptions depicted in Table 3) from early (basic) research (TRL 1) to product launched to the market (TRL 9) is about 24 to 26 months (see Figure 6a). The curve shows the behavior of negative feedback using time delay function, showing stepper improvement on early stage and gentler increment on the end of the stage.

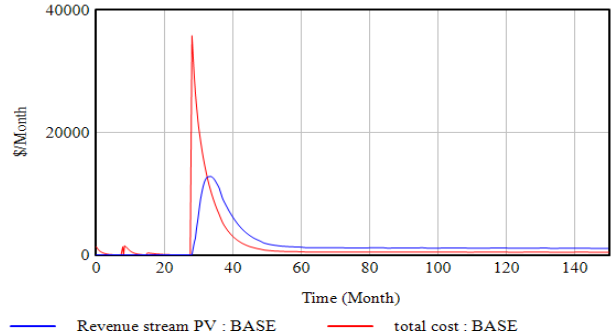
When the product is launched to the market, the product is then assessed through its quality and compared to the competitor's product. Figure 6b illustrates the simulation result showing revenue stream and the total cost. In the 25th to 30th month, the cost is higher than the revenue; it is expected that the company should do huge endeavor to introduce product to the market (i.e., the marketing cost is very high). Starting after the 30th month, the revenue is higher than the total cost, indicating the effect of the market acquisition process.

Next, Figure 6c shows the NPIC curve. Note that after a certain point of time, the break-even point is achieved. The investment cumulative and cost in production will be compensated around 92nd to 93rd month, or after 7.5 years.

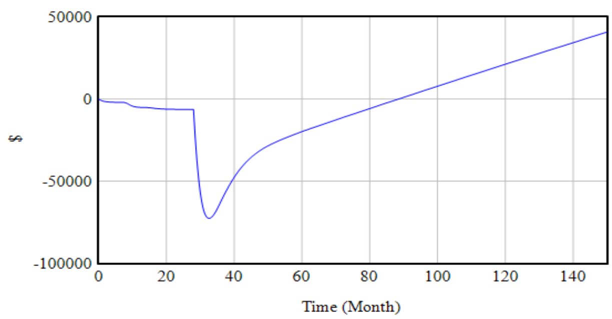
We then analyze 10 variables regarding their impact on TRL and NIPC. The result is summarized in Table 4. With these 10 variables, there would be a huge number of combinations even when each variable generates several scenarios; hence, this study does not cover all of those combinations. We only focus on three variables, i.e., (proportion) allocation to improve in lab, (proportion) allocation for innovation readiness (Habiburrahman and Ulkhaq, 2024), and product price. We generate six scenarios using these three variables. Previously, we use values in Table 3 as the baseline (i.e., (proportion) allocation to improve in lab is 1 (or 100%), (proportion) allocation for innovation readiness is 100%, and product price is only 35$). The first scenario is when all allocations are 70% but the product price remains the same. The second scenario is when allocations are 30% but the product price remains the same. The third scenario is when all allocations are 70% and the product price is getting lower (i.e., 15$). The fourth scenario is when all allocations are 70% but the product price is getting higher (i.e., 60$). The fifth scenario is when all allocations are 30% but the product price is getting lower (15$). The last scenario is when all allocations are 30% but the product price is getting higher (60$). The summary is shown in Table 5. The result shows that in the baseline model, TRL 9 is achieved around 24 to 26 months. In Scenario 1, TRL 9 is achieved around 51 to 52 months. In Scenario 2, TRL 9 is achieved longer, around 120 months or about 3 times longer than the baseline condition. Figure 7 shows the simulation results.



a. Time needed from TRL 1 to TRL 9



b. Revenue vs. total cost



c. Net present investment curve

Figure 6. Simulation result.

Table 4. Expected impacts on TRL and NPIC

No	Variables	Expected impact on TRL	Expected impact on NPIC
1	Adjustment in lab unit cost	Higher value leads to longer time to increase TRL	Higher value leads to longer time to achieve break-even point
2	Adjustment in readiness unit cost	Higher value leads to longer time to increase TRL	Higher value leads to longer time to achieve break-even point
3	(Proportion) allocation to improve in lab	Lower value leads to longer time to increase TRL	lower value leads to longer time to achieve break-even point
4	(Proportion) allocation for innovation readiness	Lower value leads to longer time to increase TRL	lower value leads to longer time to achieve break-even point
5	Time for basic research	Higher value leads to longer time to increase TRL	Higher value leads to longer time to achieve break-even point
6	Normal time to improve in lab	Higher value leads to longer time to increase TRL	Higher value leads to longer time to achieve break-even point
7	Normal time to improve to readiness	Higher value leads to longer time to increase TRL	Higher value leads to longer time to achieve break-even point
8	Product price	No impact on TRL	Higher value leads to shorten time to achieve break-even point
9	Production cost share	No impact on TRL	Higher value leads to shorten time to achieve break-even point
10	Discount factor	No impact on TRL	Lower value leads to shorten time to achieve break-even point

Next, these six scenarios are run to investigate their impacts on NPIC. The result (see Figure 8) shows that only three scenarios that never achieve break-even point, i.e., Scenario 2, Scenario 3, and Scenario 5. This condition is as expected (see Table 4—when the price is lower, it is longer to achieve break-even point). This result might give an insight to the decision maker to set product price so that lower break-even point will be obtained.

Table 5. Scenarios generated

No	Variables	Base	Sce-nario 1	Sce-nario 2	Sce-nario 3	Sce-nario 4	Sce-nario 5	Sce-nario 6
1	(Proportion) allocation to improve in lab	1	70%	30%	70%	70%	30%	30%
2	(Proportion) allocation for innovation readiness	1	70%	30%	70%	70%	30%	30%
3	Product price ($)	35	35	35	15	60	15	60

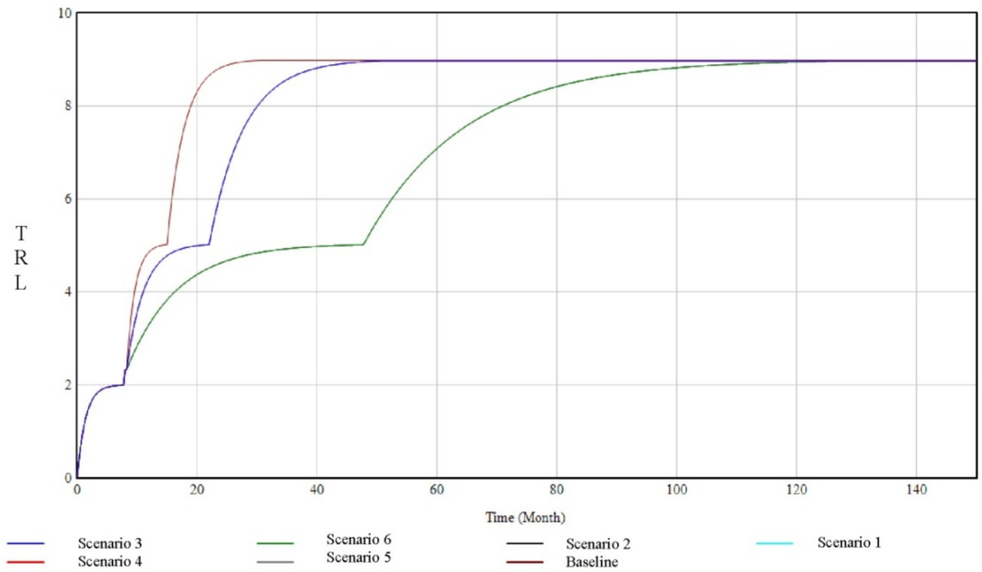


Figure 7. Simulation result: Impact on TRL

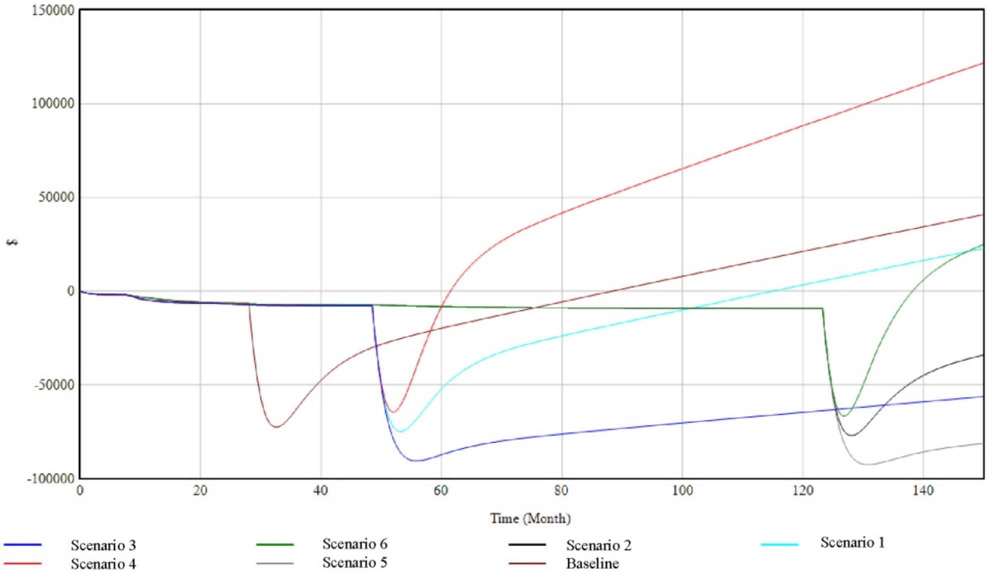


Figure 8. Simulation result: Impact on NPIC.

4.3 Discussion

The numerical analysis presented in this study reveals significant insights into the technology and knowledge transfer process, particularly regarding the advancement through technology readiness levels (TRL) and investment dynamics. Our simulation results indicate that the average time to transition from TRL 1 to TRL 9 is approximately 24 to 26 months. This timeframe aligns closely with existing literature that suggests the maturation of technology can take several years, highlighting persistent challenges in moving innovations from concept to market (Bozeman *et al.*, 2015; Aparicio *et al.*, 2016). Mankins (1995) also emphasizes the importance of systematic evaluations, noting that careful assessments at each TRL are essential for effective commercialization.

However, our findings also illuminate important implications for investment in technology transfer. The sensitivity analysis conducted indicates that even minor adjustments in resource allocation can lead to considerable variations in the TRL advancement timeline. This finding supports Hamilton's (2017) conclusion regarding the pivotal role of financial resource planning in ensuring successful technology transfer. Moreover, our results echo the work of Rubens *et al.* (2017), who argue that targeted investments in key areas of development can significantly accelerate the commercialization process. This suggests that stakeholders should prioritize funding strategies that focus on critical phases of technology development to maximize efficiency.

While the numerical analysis offers a solid foundation for understanding technology transfer dynamics, it is imperative to critically evaluate these findings in light of the broader literature. For example, while our model suggests that effective coordination among stakeholders can minimize delays in TRL progression, research by Dolmans *et al.* (2023) highlights the potential for misalignment in objectives among different stakeholders to create significant bottlenecks. This discrepancy points to the need for further exploration of how stakeholder engagement strategies can be optimized. Good *et al.* (2019) emphasizes the importance of aligning stakeholder interests and fostering collaborative environments to improve the efficiency of technology transfer initiatives.

Furthermore, our findings raise important questions about the broader market context influencing technology commercialization. The market dynamics surrounding new technologies are often complex and multifaceted. Although our model provides insights into the relationship between TRL and investment, it does not fully account for external factors impacting market readiness. Wu *et al.* (2022) argue that competitive pressures and regulatory environments significantly affect investment decisions and overall success in technology transfer. Therefore, future research should consider integrating market analysis frameworks that explore how various external conditions, such as economic trends and regulatory changes, affect technology transfer success (Xiao *et al.*, 2018).

Additionally, the implications of our findings extend beyond academic discourse to inform practical strategies for technology commercialization. For instance, policymakers should consider creating supportive environments that facilitate investment in early-stage technologies, potentially through grants or tax incentives aimed at reducing financial risk. By providing targeted support to areas identified as critical in our analysis, such as R&D and stakeholder engagement, stakeholders can foster a more conducive atmosphere for innovation and commercialization.

Furthermore, the implications of our findings extend beyond academic discourse to inform practical strategies for technology commercialization. Policymakers should consider creating supportive environments that facilitate investment in early-stage technologies, potentially through grants or tax incentives aimed at reducing financial risk. By providing targeted support to areas identified as critical in our analysis, such as R&D and stakeholder engagement, stakeholders can foster a more conducive atmosphere for innovation and commercialization. For instance, Jucevicius *et al.* (2016) emphasize the importance of creating a robust innovation ecosystem to bridge the "valley of death," where many promising technologies fail to reach the market.

In summary, while the numerical analysis offers valuable insights into the technology transfer process, it is essential to engage in a more robust discussion that integrates these findings with existing literature to draw meaningful implications. By critically examining our results within the broader academic context, we can provide nuanced recommendations for practitioners and policymakers aiming to enhance technology commercialization efforts. Addressing these complexities not only enriches academic knowledge but also equips stakeholders with practical strategies to improve the effectiveness of technology transfer initiatives across various sectors (Etzkowitz, 1998).

5. CONCLUSION, RESEARCH IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH DIRECTION

5.1 Conclusion

This study has successfully employed a SD framework to model the technology and knowledge transfer process from research to commercialization, providing valuable insights into the complexities of this critical transition. By constructing a dynamic model that captures the interactions between various stakeholders, resources, and processes, we demonstrate that the SD framework is a powerful tool for simulating the intricate relationships that underpin successful technology transfer. The findings indicate that by visualizing these relationships through CLD and SFD, stakeholders can better understand the feedback mechanisms and delays that influence TRL advancement.

Our analysis reveals that changes in key variables, such as resource allocation and product pricing, have a significant impact on the development of TRL and the overall activities involved in the technology and knowledge transfer process. Specifically, we found that targeted investments in specific areas can lead to faster TRL progression, while inefficient resource allocation can result in delays. Additionally, our simulations showed that adjusting product pricing strategies can influence market competitiveness and investment returns, thereby affecting the pace of commercialization. These insights underline the importance of strategic financial planning and resource management in facilitating successful technology transfer.

Furthermore, this research highlights the value of modeling various policy scenarios to accelerate the commercialization of academic research. By simulating different funding strategies, regulatory frameworks, and stakeholder engagement approaches, we can identify optimal pathways for reducing time-to-market and enhancing the effectiveness of technology transfer initiatives. The results suggest that tailored policies that align stakeholder interests and foster collaboration are essential for creating a conducive environment for innovation and commercialization.

In conclusion, the use of the SD framework not only enriches our understanding of the technology transfer process but also provides actionable insights for practitioners and policymakers. By addressing the research questions posed in this study, we contribute to the growing body of knowledge on technology transfer and offer strategic recommendations that can enhance the effectiveness of efforts to translate academic research into market-ready technologies.

5.2 Research Implications

The findings of this study have significant implications for research, practice, and society. By demonstrating the critical role of strategic resource allocation in advancing technology through TRLs, this research contributes to the body of knowledge surrounding technology transfer and commercialization (Hamilton, 2017). It emphasizes the need for policymakers and industry leaders to develop comprehensive strategies that prioritize investment in key areas of technology development, ultimately enhancing innovation ecosystems (Rubens *et al.*, 2017).

From a practical perspective, this study highlights the importance of effective stakeholder coordination and communication. Establishing clear goals and aligning interests among researchers, investors, and industry partners can lead to more successful outcomes in technology commercialization (Xiao *et al.*, 2018). Furthermore, the research underscores the necessity of creating supportive environments that foster innovation and facilitate investment in early-stage technologies, which can ultimately influence public attitudes toward new technologies and improve overall quality of life (Etzkowitz, 1998). This research also offers a strategic platform for understanding the complexities of technology transfer and the factors influencing its success.

5.3 Limitations

While this study provides valuable insights into the technology transfer process through SD modeling, several limitations must be acknowledged. Firstly, the model relies on assumptions that may not fully capture the complexities of real-world scenarios. For instance, the dynamics of stakeholder interactions were simplified to focus on primary relationships, potentially overlooking intricate social factors that could influence technology and knowledge transfer outcomes (Dolmans *et al.*, 2023). Additionally, the availability and accuracy of data used in the simulations can affect the validity of the results.

5.4 Future Research Directions

To build upon the findings of this study, several research directions are suggested. One potential direction is to investigate the influence of external factors, such as market conditions and regulatory environments, on the technology transfer process. Incorporating these elements into the SD model could enhance its applicability and robustness (Wu *et al.*, 2022). Furthermore, future studies could explore how varying stakeholder engagement strategies affect the success of technology transfer initiatives. Research by Good *et al.* (2019) emphasizes the necessity of aligning stakeholder interests, which can lead to improved efficiency in technology transfer. Additionally, examining the long-term effects of technology transfer on economic growth and public policy could provide deeper insights into the broader implications of successful commercialization (Bozeman *et al.*, 2015).

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REFERENCES

Abreu, M., Demirel, P., Grinevich, V., and Karataş-

Özkan, M. (2016), Entrepreneurial practices in research-intensive and teaching-led universities, *Small Business Economics*, **47**, 695-717.

Agasisti, T., Barra, C., and Zotti, R. (2019), Research, knowledge transfer, and innovation: The effect of Italian universities' efficiency on local economic development 2006–2012, *Journal of Regional Science*, **59**(5), 819-849.

Alamerew, Y. A. and Brissaud, D. (2020), Modelling reverse supply chain through system dynamics for realizing the transition towards the circular economy: A case study on electric vehicle batteries, *Journal of Cleaner Production*, **254**, 120025.

Algieri, B., Aquino, A., and Succurro, M. (2013), Technology transfer offices and academic spin-off creation: The case of Italy, *The Journal of Technology Transfer*, **38**(4), 382-400.

Aparicio, S., Urbano, D., Gómez, D. (2016), The role of innovative entrepreneurship within Colombian business cycle scenarios: A system dynamics approach, *Futures,* **81**, 130-147.

Ardiyawan, R. and Ulkhaq, M. M. (2024), System dynamics modelling for municipal solid waste management - A literature review, *International Journal of Academic Multidisciplinary Research*, **8**(4), 207-216.

Bala, B. K., Arshad, F. M., and Noh, K. M. (2018), *System Dynamics: Modelling and Simulation,* Springer.

Bozeman, B., Rimes, H., and Youtie, J. (2015), The evolving state-of-the-art in technology transfer research: Revisiting the contingent effectiveness model, *Research Policy,* **44**(1), 34-49.

Branscomb, L. M., Kodama, F., and Florida, R. (1999), *Industrializing Knowledge. University-Industry Linkages in Japan and the United States*, MIT Press.

Capaldo, G., Costantino, N., Pellegrino, R., and Rippa, P. (2016), Factors affecting the diffusion and success of collaborative interactions between university and industry: The case of research services, *Journal of Science and Technology Policy Management*, **7**(3), 273-288.

De Jong, S., Barker, K., Cox, D., Sveinsdottir, T., and Van den Besselaar, P. (2014), Understanding societal impact through productive interactions: ICT research as a case, *Research Evaluation*, **23**(2), 89-102.

Dolmans, S. A. M., Walrave, B., Read, S., and van Stijn, N. (2023), Knowledge transfer to industry: how academic researchers learn to become boundary spanners during academic engagement, *Journal of Technology Transfer*, **47**(5), 1422-1450.

Etzkowitz, H. (1998), The norms of entrepreneurial science: Cognitive effects of the new university– industry linkages, *Research Policy*, **27**(8), 823-833.

Forrester, J. W. (1958), Industrial dynamics: A major breakthrough for decision makers, *Harvard Business Review*, **36**(4), 37-66.

Good, M., Knockaert, M., Soppe, B., and Wright, M. (2019), The technology transfer ecosystem in academia. An Organizational Design Perspective, *Technovation,* **82**, 35-50.

Habiburrahman, R. and Ulkhaq, M. M. (2024), Innovation readiness analysis of battery electric vehicle: A case of gesits G1, *Proceeding International Conference on Religion, Science and Education,* **3**, 551-559.

Hamilton, C. (2017), Emerging research institutions' technology transfer supply chain networks' sustainability: Budget resource planning tool development, *IEEE Engineering Management Review,* **45**(4), 39-52.

Jucevicius, G., Juceviciene, R., Gaidelys, V., and Kalman, A. (2016), The emerging innovation ecosystems and "Valley of death": Towards the combination of entrepreneurial and institutional approaches, *Engineering Economics*, **27**(4), 430-438.

Krivtsov, V., Pluchinotta, I., and Pagano, A. (2023), Teaching systems thinking and system dynamics in engineering, ecology and environmental sciences: A concise course based on the water management and population dynamics models, *International Journal of Environmental Impacts,* **6**(1), 25-36

Lee, H. K., Youm, H. D., Kim, S. J., Suh, Y. K. (2016), Factors affecting university–industry cooperation performance: Study of the mediating effects of government and enterprise support, *Journal of Science and Technology Policy Management*, **7**(2), 233-254.

Liu, J., Liu, Y., and Wang, X. (2020), An environmental assessment model of construction and demolition waste based on system dynamics: A case study in Guangzhou, *Environmental Science and Pollution Research,* **27**(30), 37237-37259.

Mankins, J. C. (1995), *Technology readiness assessments: A summary of current practices*, Office of Space Access and Technology, NASA.

Molas-Gallart, J. and Castro-Martínez, E. (2007), Ambiguity and confict in the development of 'Tird Mission' indicators, *Research Evaluation,* **16**(4), 321-330.

Mongeon, P. and Paul-Hus, A. (2016), The journal coverage of Web of Science and Scopus: A comparative analysis, *Scientometrics*, **106**(1), 213-228.

Pinha, A. C. H. and Sagawa, J. K. (2020), A system dynamics modelling approach for municipal solid waste management and financial analysis, *Journal of Cleaner Production*, **269**, 122350.

Pujotomo, D., Syed Hassan, S. A. H., Ma'aram, A., and Sutopo, W. (2023), University–industry collaboration in the technology development and technology commercialization stage: A systematic literature review, *Journal of Applied Research in Higher Educa-*

tion, **15**(5), 1276-1306.

Rebs, T., Brandenburg, M., and Seuring, S. (2019), System dynamics modeling for sustainable supply chain management: A literature review and systems thinking approach, *Journal of Cleaner Production*, **208**, 1265-1280.

Rubens, A., Spigarelli, F., Cavicchi, A., and Rinaldi, C. (2017), Universities' third mission and the entrepreneurial university and the challenges they bring to higher education institutions, *Journal of Enterprising Communities: People and Places in the Global Economy*, 11(03), 354-372.

Saunders, M., Lewis, P., and Thornhill, A. (2012), *Research Methods for Business Students* (6th ed.), Pearson, London.

Secundo, G., De Beer, C., and Passiante, G. (2016), Measuring university technology transfer efficiency: A maturity level approach, *Measuring Business Excellence*, **20**(3), 42-54.

Sterman, J. D. (2000), *Business Dynamic. Systems Thinking and Modelling for a Complex World*, McGraw-Hil, New York.

Su, D., Zhou, D., Liu, C., and Kong, L. (2015), Government-driven university-industry linkages in an emerging country: The case of China, *Journal of Science and Technology Policy Management*, **6**(3), 263-282.

Turner, B. L., Menendez III, H. M., Gates, R., Tedeschi, L. O., and Atzori, A. S. (2016), System dynamics modeling for agricultural and natural resource management issues: Review of some past cases and forecasting future roles, *Resources*, **5**(4), 40.

Urdari, C., Farcas, T. V., and Tiron-Tudor, A. (2017), Assessing the legitimacy of HEIs' contributions to society: The perspective of international rankings, *Sustainability Accounting, Management and Policy Journal*, **8**(2), 191-215.

Walters, J. P., Archer, D. W., Sassenrath, G. F., Hendrickson, J. R., Hanson, J. D., Halloran, J. M., ... and Alarcon, V. J. (2016), Exploring agricultural production systems and their fundamental components with system dynamics modeling, *Ecological Modelling,* **333**, 51-65.

Wu, J. and Shang, S. (2019), Modelling tacit knowledge transfer in MOOCs: Simulations on the transfer process, *HKIE Transactions Hong Kong Institution of Engineers,* **26**(3), 126-135

Wu, Y., Gu, X., Tu, Z., and Zhang, Z. (2022), System dynamic analysis on industry-university-research institute synergetic innovation process based on knowledge flow, *Scientometrics,* **127**(3), 1317-1338.

Xia, J., Liu, W., Tsai, S. B., Li, G., Chu, C. C., and Wang, K. (2018), A system dynamics framework for academic entrepreneurship, *Sustainability*, **10**(7), 1-25.

Xiao, L., Xu, S., and Zeng, X. (2018), Design and analysis of knowledge transfer in the process of university-industry collaborative innovation based on social network theory, *Journal of Internet Technology,* **19**(4), 1155-1167.

Yoon, D. (2017), The regional-innovation cluster policy for R&D efficiency and the creative economy: with a focus on Daedeok Innopolis, *Journal of Science and Technology Policy Management*, **8**(2), 206-226.

Zhai, H. (2013), Knowledge transfer in engineering and technology education in universities, *World Transactions on Engineering and Technology Education,* **11**(2), 76-81.

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