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Interdisciplinary Transition Innovation, Management, and Engineering (InTIME) Design: an intersection analysis of design approaches for whole-system sustainability

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Abstract

Interdisciplinary transition innovation, management, and engineering (InTIME) Design has been developed to overcome sustainability transition challenges in complex systems. The intersections of InTIME Design with a range of reported design for sustainability (DfS) approaches were analysed. Results demonstrate similar core principles across DfS approaches. InTIME Design accomplishes convergence of the studied approaches, and organises the DfS approaches into workflow phases, adds a complimentary wicked problem definition, and deploys systems engineering problem solving.

Keywords: design process, whole-system sustainability, transition engineering, sustainable design

1. Introduction

The mega problems of anthropogenic unsustainability originate in the design, emergence, and operation of successful socio-technological systems (STSs) (Steffen et al., 2020). STSs comprise human-made, engineered systems employing technology and operational management for industrial scale energy, manufacturing, agriculture, transport, or buildings (Creutzig et al., 2016). STSs appropriate energy and resources for designing, producing, and delivering artifacts to the market. The entire value chain from extraction to disposal emits waste products into the environment, driving unsustainable exponentially increasing atmospheric CO2 concentration, biodiversity loss, and ocean acidification (Steffen et al., 2015). Transition of incumbent STSs to sustainable energy, material supply chains, and product lifecycles requires a whole-systems perspective. But designing a pivot for an STS presents wicked and complex problems (Seager et al., 2012), with high first mover risks because business as usual (BAU) is a preferred economic option.

Green design, eco-design, and design for sustainability (DfS) have progressed over the past thirty years (Ceschin and Gaziulusoy, 2016). However, the climate, ecological, and biodiversity emergencies have accelerated faster. Is it possible that a corrective engineering and management discipline, like safety and risk management, could drive STSs pivot to net zero, and social/environmental sustainability? A convergence of DfS approaches with engineering and management decision-making processes could be the route to such a new and impactful corrective transdiscipline. A challenge in the sustainability field remains that the advances in sustainability science and DfS need to be accelerated and delivered at scale for achieving the required downshift of unsustainability of STSs. The gap in the delivery of whole system sustainability is the absence of an established discipline that brings the DfS practice into engineering delivery.

Design is the work of "changing existing situations into preferred ones" (Simon, 1996), including pursuing answers to wicked problems of sustainability (Irwin, 2018). DfS has evolved from making products greener towards whole-system sustainability (Ceschin and Gaziulusoy, 2016). Engineering disciplines will play a major role in delivering the required whole-system changes (Allenby, 2000; Kroes et al., 2006). Historically, corrective engineering transdisciplines have evolved in response to catastrophic failures in BAU operations for delivering safety, security and risk management by preventing what is preventable. Transdisciplines combine engineering methods, design, business models, and behaviour by focusing on the mission underpinned by collective agreement and duty of care (Krumdieck, 2022).

Transition Engineering is a corrective transdiscipline with the mission to downshift unsustainable energy and materials flows in STS operation to within planetary safety margins (Krumdieck, 2019). The field of Transition Engineering emerged over the last 2 decades as a collaborative academic and professional exploration of "how do we" deliver the urgently needed re-design to downshift unsustainable aspects of STSs (GATE, 2023; The Shift Project, 2023). Transition Engineering employs systems approaches, and a seven-step systemic design approach that broadens perspectives while focusing on resolving the underlying issues at the heart of wicked problems (McMahon and Krumdieck, 2022). The seven-step approach is called Interdisciplinary Transition Innovation, Management and Engineering (InTIME) Design, and has been developed through research and practice.

The research question is: Could the current practices aimed at design for whole system sustainability be brought together into a coherent approach that captures the expertise and experiences and creates a new transdisciplinary route to impact? Our hypothesis is that the InTIME Design approach can provide a framework for convergence of DfS approaches into an engineering transdiscipline. We examine this hypothesis by analysing the intersections of operational steps between whole-system sustainability design approaches and InTIME Design.

2. Background: InTIME Design approach

InTIME Design has been demonstrated over the last decade with use cases in agriculture, building heat, personal transport and urban form, remote energy, demand participation, and freight transport, and has resulted in path breaking shift project concepts (Ahrens et al., 2022; Andrade et al., 2022; Bai and Krumdieck, 2020; Blair et al., 2019; Fulhu et al., 2019; Gallardo et al., 2021; Gyamfi and Krumdieck, 2011; Krumdieck, 2019, 2015; Krumdieck and Hamm, 2009). New types of data infrastructure that expands understanding of current systems and sources of unsustainability are often more advantageous shift projects than new energy technologies. Modelling formulates future value propositions, visualises new urban form, and assesses technology or policy potentials. InTIME Design problems and requirements are defined by flipping the perspective to downshift of unsustainable activities rather than seeking "more sustainable solutions".

2.1. Workflow phases

Transition Engineering starts with the definition of the wicked problem for a specific place and needs of stakeholders. Figure 1 shows the three phases of InTIME Design, Management, Innovation, and Engineering. The Management Phase focuses on the STS and the whole-system context of the specific problem. The Management Phase aims to establish understanding of how the system works and how locked-in unsustainability has emerged. Data about the end uses, supply chains, finance, business models, governance, behaviour, technology, and policy are investigated. The Management Phase also investigate incumbent strategies, targets, plans and future scenarios.

The Innovation Phase recognises that BAU scenarios do not lead to viable sustainable futures for the STS or the context in which the STS operates. There is no recipe for innovation, but ingenuity can be supported by purposeful convergent and divergent thinking activities, freed up from conventions and agendas, but bounded by the requirement of maintaining essential needs in the transition process. Innovation to diverge from BAU will challenge the current business model of the STS. The Innovation Phase includes path break and sandbox work which is purposefully creative and subjected to the hard constraints of strong sustainability (Nikolaou et al., 2019).

The Engineering Phase uses the data and path break ideas, together with strategic systems analysis of options involving stakeholders, research, and modelling for developing proposals for shift projects. The

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Engineering Phase deploys foresight and critical thinking about the future implications for the development and delivery at scale of the preferred project.

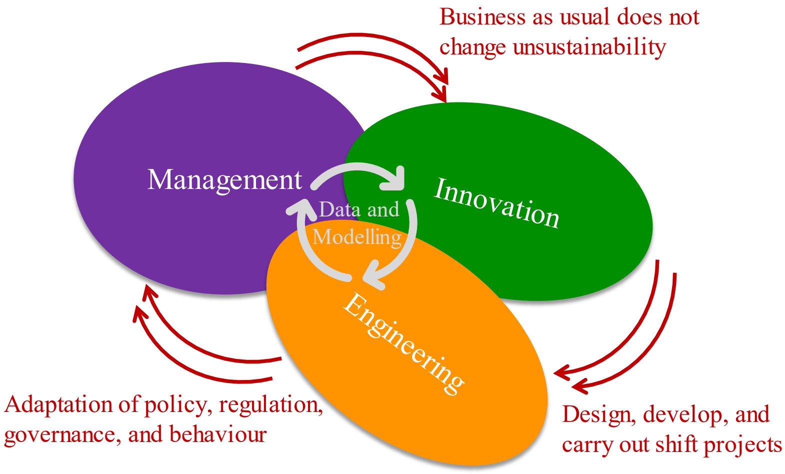

Figure 1. The 3 phases of the Transition Engineering framework (further developed from (Krumdieck, 2019))

2.2. InTIME Design approach

InTIME Design includes the preliminary Discovery Phase and organises the seven main steps and several sub-steps into three phases as shown in figure 2. The steps have evolved from interdisciplinary perspectives on engineering design and research, systems thinking, and professional change projects (Krumdieck, 2019).

Discovery Phase step 0 - Wicked problem investigation

The preparatory wicked problem investigation aims to redefine the project objectives in terms of designing changes to the drivers and accelerators of unsustainability with stakeholders and experts. The investigation activity defines the problem from the different perspectives of why the specific system is still functional, why it is unsustainable, what needs are satisfied, what harms are caused, what green solutions exist, and why the system cannot change still. Wicked problems require a non-reductionistic, whole systems approach for problem solving from technology, economics, policy, governance, and ontology (Irwin, 2018). The preliminary step defines the activity system in a specific place, social and geographical context, political and environmental attributes, and the STSs involved. A wicked problem is posed by a human activity system that uses successful technology and energy, but that also has locked-in unsustainability and generates unacceptable harms. Wicked problems are common in transport, built environment, infrastructure, manufacturing, education, or health care (Krumdieck, 2019). Activity systems emerged purposefully to meet essential needs such as access to social interaction, well-being, education, or shelter (Max-Neef, 1992), require energy and resources to operate, and intersect with the natural environment through fuels, electricity, and materials (Steffen et al., 2020). A wicked problem arises if the sustainability challenges to the system risk the satisfaction of essential, ground-level human needs. Essential needs are universal but the specific manifestation varies between places, which adds the spatial component to the definition of the problem (Mistry and Berardi, 2016).

Management Phase step 1 - History

The first step of InTIME Design is a "time travel" to the location of inquiry in 1911. The technology, social, and economic contexts of how people met their essential needs are studied. STS transition can only be fully understood if the history of the system and its actors are understood (Silva et al., 2022). Historical research is carried out to build a narrative of how the essential activity was carried out in the past with generally less resource and energy throughput. Historical landmark changes over the past century are identified to understand why and how technology, markets, and other whole-system context changed. Landmark changes can be efficiency innovations, disruptive technologies, economic crises, resource depletion, or the discovery of new resources (i.e., switch from coal to natural gas, oil and the internal combustion engine, OPEC oil embargo).

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Management Phase step 2 - Present

The present system analysis includes taking qualitative and quantitative stock of interconnected energy and resource consumption, policy, governance, and behaviour landscapes surrounding the essential activity (Meadows and Wright, 2008). The aim of step 2 is to get a clear view of the status and the plans for the immediate future in response to environment, energy, or social pressures. The current strategies, policies, and investments going forward are examined. Data analysis of existing data or the generation of new data sets through data exchange might be required for understanding performance, unsustainability, behaviours, impacts, and costs in the local and national system context. Sources of data can be local and traditional knowledge, geospatial data, input-output analyses, or carbon accounting.

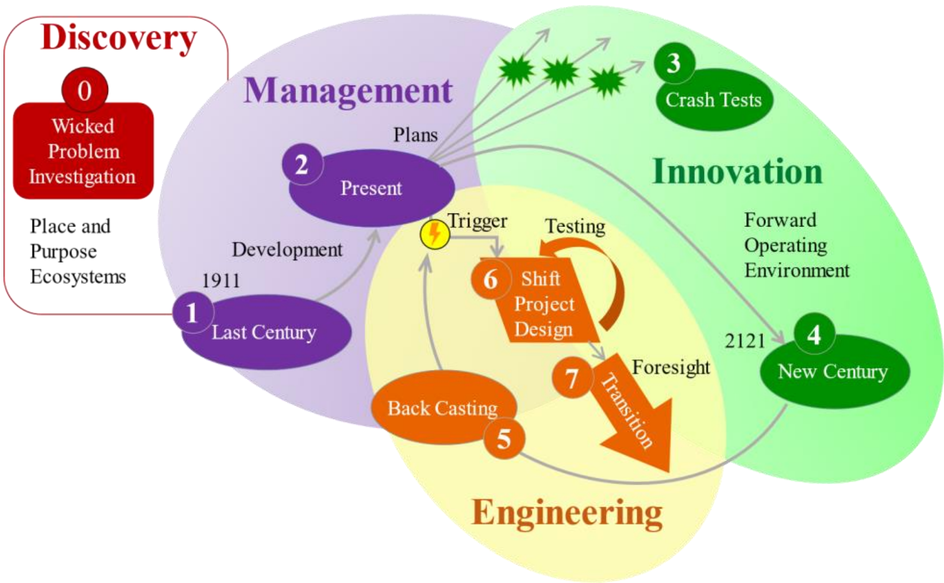

Figure 2. The Discovery Phase and the 7 steps of InTIME Design grouped by workflow phases (further developed from (Krumdieck, 2019))

Innovation Phase step 3 - Future scenario crash tests

Step 3 looks at the future of the system along different trajectories characterised by the current STS strategies and plans. Future scenarios are systemically "crash tested" using risk analysis techniques to assess if the scenario futures address the wicked problem. The risks of unsustainability are examined using biophysical economics (King and van den Bergh, 2018). Current infrastructures and business models are assessed for their supportability of the future scenarios (Watari et al., 2022). The BAU scenario is the continuation of current trajectories, or government and corporate policies. The technology scenario explores the effects of incentives and policies regarding uptake and scale of green technology market penetration. The efficiency scenario investigates sustainability effects of policy and business steps to improve circularity or footprint. The behaviour scenario examines the effect of environmental behaviour change incentives.

Innovation Phase step 4 - Path break

Biophysical and social sustainability limits create a path break forward-operating-environment that arrives at the system 100 years in the future. A vision is established where the tensions around the wicked problem have been resolved, the essential needs are still met, and the unsustainable consumption of energy and resources has downshifted to support survival in a thriving world. The usual method is a creative "time travel" exploration to the place of inquiry, focusing on observations of what is the same and what is done differently along the sustainable transition. The sustainable future is an engineering-informed sandbox of possibilities bound by thermodynamic and biophysical limits (Kim and Oki, 2011). The question asked in this step is "How does the system operate in 100 years while equitably meeting essential needs with safe levels of energy and resource consumption?". Rules for the path break time travel are that doomsday scenarios and undemonstrated technologies are set aside.

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Engineering Phase step 5 - Back casting and triggers
Back casting determines the necessary steps between a future vision and now to realise the envisioned future scenario (Robinson, 1990). Back casting supports breaking with path-dependencies of BAU scenario forecasting methods (Irwin, 2018; Meadows and Wright, 2008). A key question for Transition Engineering is "What do the people in the path-break future have that we currently do not have?" (i.e., market rules, financial institutions, regulations, norms, infrastructure, or technology). The potential trigger events for initiating a path break innovation in the present are investigated. COVID-19, the Russian invasion in Ukraine, and unprecedented climate disasters could be triggers, but so could business model pivots and innovations (i.e., moratoriums on oil and gas development, carbon taxes, or changes to law and regulations).
Engineering Phase step 6 - Shift project
A range of project concepts are developed by the Transition Engineering team for creating a step change or shift in the current system regarding the unsustainable activity. A preferred option is chosen using multicriteria analysis which incorporates sustainability indicators such as carbon emissions, energy security, biodiversity, economic development, and ecological conservation to achieve well-being in a thriving environment. A project brief is developed with stakeholders containing the concept, timeline, and resources for implementing the designed innovation project. The brief is used to leverage funding, make a business case, or justify the need for further research. The shift project plan includes learning and improvement when it is carried out. The performance of the implemented changes is observed and monitored using an action research approach. The shift projects provides navigation for steering the complex system with evaluation of position and adaptation of direction (Meadows and Wright, 2008).
Engineering Phase step 7 - Transition foresight
The learnings from the shift project are used to critically examine the system transitions that could follow from development of the project at scale. The transition impacts may take years to unfold and interact with the myriad other system interventions (Geels et al., 2017). The step applies strategic foresight to the implications of a successful shift project before the policy or investment at scale is committed. The potential impacts of the shift project on policy, technology, society, economy, governance, media, or the environment are investigated to mitigate unintended consequences.

3. Method: Intersection analysis for DfS approaches

The intersection analysis method compares contextual similarity or parity of purpose of processes and steps in different design approaches using published descriptions of the processes and the steps. The intersection analysis will support the hypothesis that current design approaches for whole-system sustainability can be brought together, if InTIME Design encompasses other DfS approaches or could be further expanded to include additional operations. Figure 3 graphically illustrates the exemplary intersection analysis between InTIME Design and The Framework for Strategic Sustainable Development (Broman and Robèrt, 2017).
Steps with strong intersection share methods and principles. Steps with medium intersection share the general approach but do not include some elements of the InTIME Design steps. The decision for strong, medium, or no intersection is qualitative. A step from a published design approach does not necessarily need to use the same InTIME step name to be considered as intersecting.
The analysed design approaches were identified by conducting literature research in Scopus with the keywords "*design for sustainability", "systemic design", "process", and "approach"* considering the criteria: 1) whole-system sustainability approach, 2) design-led development of innovation projects, 3) clear outline of the design methods that go beyond frameworks of design principles, and 4) focus on *creating* projects, products, systems, or services for whole-system sustainability. The considered design approaches were from design, management, and engineering. In the context of this paper, whole-system sustainability is defined as a system property for meeting current and future human needs, and not transgressing planetary boundaries and ecosystem resilience. Approaches also have methods, tools, and principles and can be embedded in applications such as living labs. However, the investigation excludes the upstream methods, tools, and principles and the downstream real-world application. Design approaches for sustainability as an add-on or "end of pipe" for products and services are not considered.

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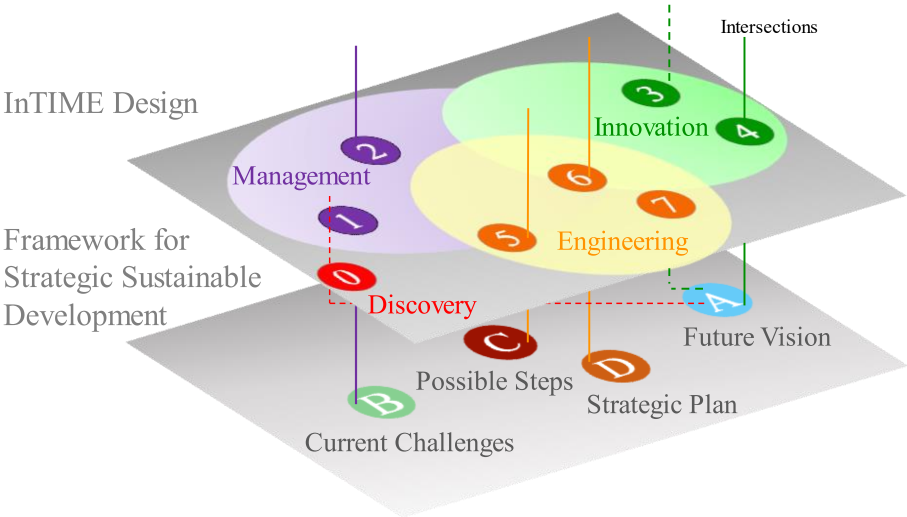

Figure 3. Intersection analysis method example with the Framework for Strategic Sustainable Development (Broman and Robèrt, 2017); Solid lines indicate a strong intersection, dashed lines indicate a medium intersection

4. Results: InTIME Design intersection analysis

The selected design approaches from literature are: Framework for Strategic Sustainable Development (Broman and Robèrt, 2017), Transition Design (Irwin, 2018), Transition Management (Nevens et al., 2013; Rotmans et al., 2001), Integrated Sustainable Engineering Design (Gagnon et al., 2012), Systemic Design Approach (Drew et al., 2021), Sustainable Technology Development (Weaver et al., 2017), and System Innovation for Sustainability (Gaziulusoy et al., 2013). All further mentioning of the approaches from literature relate to the above given references. The Framework for Strategic Sustainable Development and System Innovation for Sustainability aim at understanding the role of organisations in sustainability, aligning the role with whole-system sustainability, and innovating business models, products, or services. Transition Design, Integrated Sustainable Engineering Design, and Systemic Design Approach are general design approaches for sustainable design from a systems and engineering perspective. Transition Management informs transformative policy and governance development. Sustainable Technology Development sets out that current techno-solutionism is unlikely to result in sustainability, and aims to develop needs-based technology products or services for whole-system sustainability innovation. The results of the intersection analysis are displayed in table 1.

The results show that most approaches and InTIME Design use a systemic problem definition method from perspectives of environment, economics, society, and technology. The system design problem focus does not lie on certain technologies or products, but on the function and purpose of systems. For example, Transition Design acknowledges the wickedness of systemic problems that require a design-led problem-solving approach. In the Transition Design problem definition step, a collaborative map is created with a systems view of infrastructure, society, politics, economics, and environmental aspect of the wicked problem. The system level properties are connected to the ground-level fears, hopes, and desires of the design stakeholders. Sustainable Technology Development provides the focus on present needs to the problem definition step, asks how needs could be met in the future, and highlights that the design approaches should be needs driven instead of technology driven. InTIME Design adds a place-based wicked problem approach that strictly starts from end use and essential activities and aims at discovering the root cause of the wicked problem.

Different levels of qualitative and quantitative system analysis are deployed to understand the system operation and interconnections. InTIME Design introduces the dedicated step of including the history of the last century, specifically 1911 in the locale of interest, in the system analysis. The history step intersects implicitly with Transition Design, Transition Management, and Systemic Design Approach which acknowledge the importance of historical data and contexts in the system analysis.

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All approaches involve present-day system analysis for taking stock of the system operation (policy, governance, technology, environment, economics), and for understanding how sustainability and unsustainability unfold in the system. For example, the Framework for Strategic Sustainable Development uses specific sustainability principles to evaluate how unsustainable the current situation is. The sustainability principles encompass renewable and fossil resource sustainability and human well-being. InTIME Design complements the system analysis step with the concept of data exchange for understanding the system around the wicked problem if data is not readily available.

Table 1. Intersection analysis of design for whole-system sustainability approaches and InTIME Design. Half-filled circles indicate medium intersection, and fully filled circles indicate strong intersection

Design approaches for whole-system sustainability	InTIME Design							
	Wicked Problem Investigation	Last Century	Present	Crash Tests	New Century	Back Cast and Trigger	Shift Project Design	Transition Foresight
Framework for Strategic Sustainable Development	0		2	3	4	5	6	
Transition Design	0	1	2		4	5	6	7
Transition Management		1	2		4	5	6	
Integrated Sustainable Engineering Design			2		4		6	
Systemic Design Approach	0	1	2		4		6	
Sustainable Technology Development	0		2	3	4	5	6	
System Innovation for Sustainability	0		2		4	5	6	

The "crash test" step can be considered a new addition to the design approaches for whole-system sustainability. The Framework for Strategic Sustainable Development and Sustainable Technology Development acknowledge the importance of assessing the feasibility for achieving sustainability of potential technologies but a detailed description of the assessment procedure could not be found in literature. InTIME Design complements a rigorous technological feasibility, biophysical sensibility, and business model opportunity assessment for BAU policy and technology propositions. Especially the biophysical analysis aspect of InTIME Design is a novel contribution to the design approaches for whole-system sustainability. The role of whole system energy and resource flows in economic activity appears to be an over-looked Design aspect in assessing future energy propositions.

All investigated approaches apply visioning and back casting methods. The reported visions are mostly future scenarios where the identified problem has been resolved, and the social needs are still met. For example, the Framework for Strategic Sustainable Development recognises the importance of material and energy sustainability constraints to the future visions. Scenario assessment or benchmarking are used for sustainability evaluation. In Transition Design a "day in the life of" activity is performed to creatively mimic life in the future. As a main difference to the Systemic Design Approach, InTIME Design does not engage in free flow visioning exercises. However, the InTIME wicked problem investigation moves the free flow visioning to the problem definition stage and collects green technology solutions to set them aside for later sensibility and feasibility assessment in the "crash test".

Back casting demonstrates the significance of using path-breaking activities for escaping the fallacies of BAU forecasting techniques. Back casting is broadly used to identify scenarios and steps for reaching the future vision from the present-day. Approaches from literature agree on using back casting for evaluating strategic transition pathways with milestones, and identification of obstacles. System Innovation for Sustainability contributes forward planning to identify how short-term actions could meet with back casted pathways. InTIME Design adds the identification of triggers after the back casting.

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The next logical step after back casting is the definition of projects or action plans for implementing the developed scenarios and concepts into products, services, technologies, policies, or governance. The project implementation is monitored to observe if the estimated outcomes are achieved, and to adapt the project plans accordingly. Iteration is required for making real-world prototypes in complex systems. For example, Transition Management and Sustainable Technology Development deploy transition experiments within development niches to stimulate implementation and acceleration.

InTIME Design complements the vision and back cast by connecting them to the physical place of inquiry for making the activity more locally tangible and actionable. Biophysical and thermodynamical rigour is applied in the sensibility and feasibility assessment of future scenarios and concepts. InTIME shift projects are based in project management and require a brief to operationalise the project. The dedicated step of defining shift projects make the InTIME designers deliberately focus on developing tangible projects as an outcome of the design activity. A contribution to the design approaches for whole-system sustainability is the step of deploying transition foresight to purposefully assess unintended consequences prior to final decisions on demonstration or development projects. However, InTIME Design does not use established frameworks for carrying out the transition foresight. For example, Transition Design highlights the importance of long-term thinking but warns that complex systems cannot be predicted. Transition Design makes the case for using the "seventh generation principle" when decisions over long time horizons have to be made.

5. Discussion and conclusion

InTIME Design was described as an emerging design practice for engineering the transitions of incumbent STSs. An intersection analysis between InTIME Design and design approaches for whole-system sustainability from literature was carried out. The investigated approaches from literature are the Framework for Strategic Sustainable Development, Transition Design, Transition Management, Integrated Sustainable Engineering Design, Systemic Design Approach, Sustainable Technology Development, and System Innovation for Sustainability. The results of the intersection analysis show that InTIME Design intersects with most of the current practices in design for whole-system sustainability. The first observation is that both InTIME Design and other design for whole-system sustainability approaches follow a general transdisciplinary sustainability research process of problem definition, co-creation of solutions, and application of knowledge (Lang et al., 2012), highlighting the connection of design, transdisciplinarity, and transformative research processes (Lawrence et al., 2022). From an engineering standpoint we argue that the design approaches for whole-system sustainability usually do not deploy rigorous scenario assessment for feasibility, possibility, and profitability (Krumdieck and Hamm, 2009). InTIME Design complements other design approaches by applying biophysical sensibility, technological feasibility, and economic opportunity evaluation to future energy and resources scenarios. The dedicated analysis of history and the "crash test" of policy and technology propositions are new additions to design for whole-system sustainability. Further novel steps are the identification of triggers after the back casting activity and the strategic foresight transition planning for identifying potential unintended consequences of the developed shift project. Transition foresight origins in systems engineering risk assessment of unintended consequences (Eckert and Clarkson, 2021). A limitation of the method is that the analysis did not set out to produce a systematic literature review of all possible design approaches for whole-system sustainability. Although rigour was applied to the literature research, it is likely that the intersection analysis does not cover every existing eligible approach. The authors also acknowledge that Design is a practical field beyond academic and research inquiry. Possibly, there are practical design approaches that elude from search in scientific data bases, and are less visible to academic eyes.

The implication of the intersection analysis is that DfS specialists from all fields could use InTIME Design to work together in a new integrative approach for achieving and engineering the transition to whole-system sustainability. We observe that design for whole-system sustainability converges to working on wicked problems, focussing on human needs, being technology agnostic, requiring feasibility analysis for potential solutions, using ingenious vision and back cast to break with current trajectories, carrying out the body of work through shift projects, and applying foresight to mitigate unintended consequences. We conclude that InTIME Design encompasses well-established practices in the field, and complements them with methods from systems engineering, systems thinking, biophysical economics, and risk management. However, InTIME Design does not yet have the workflow process of other corrective transdisciplines in engineering. An actionable process for delivering the design and outcomes to the real world is required and will be subject of further inquiry.

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