INTERNATIONAL DESIGN CONFERENCE – DESIGN 2024
https://doi.org/10.1017/pds.2024.4

Feedback thought at the intersection of systems and design science

Igor Czermainski de Oliveira ✉, Daniel Guzzo and Daniela C. A. Pigosso
Technical University of Denmark, DTU Construct, Denmark
✉ icdol@dtu.dk

Abstract
This paper explores the interplay of feedback principles in design and systems science. From their roots in engineering, biology, and economics, it investigates intersections between design, cybernetics and servomechanisms. The synthesis emphasizes the need for considering feedback in anticipating unintended consequences and proposes an integrative view reconciling fundamental assumptions from the different fields through simulation. This holistic approach underscores the pivotal role of feedback in understanding and addressing complex phenomena, such as rebound effects, in design science.

Keywords: complex systems, design theory, design methods, design models, feedback

1. Introduction

As one ventures through various methodological and theoretical intersections, feedback's importance in explaining and crafting complex systems becomes evident. The dual nature of feedback - as both a descriptive and prescriptive force in design science - arises (Simon, 1952; Midgley, 2000). It informs the understanding of systems and guides their creation, refinement, and evolution (Richardson, 1991). The term 'feedback', originating from the realm of engineering, denotes a system's capability to regulate itself by responding to changes in its environment or its own output (Wiener, 1948; Bertalanffy, 1968). This concept has profoundly influenced various disciplines, notably within the social sciences and design science - a field inherently concerned with the artificial and the creation of human-made systems (Simon, 1969). Although systems and design sciences share ideas and purposes, the convergences are not clearly mapped. The concepts of systemic design (Jones, 2014), design for systems innovation (Gaziulusoy and Brezet, 2015; Ceschin and Gaziulusoy, 2016), as well as frameworks for integrating systems and design (Poudehnad et al., 2011; Pohl et al., 2020), are examples of attempts to articulate both disciplines. However, not much attention has been given to the phenomenon in design beyond the early cybernetic definitions of feedback as a link between an engineered system's input and its output. We hypothesize this might limit the identification and mitigation of unintended consequences of design practices, such as rebound effects, due to lack of consideration of the societal and biological dynamic complexities at stake, especially when it comes to contemporary challenges (Guzzo et al., 2023, 2024). This paper explores the intersections of feedback principles within the context of design and systems sciences, reflecting on historical perspectives. By doing that, this paper has a two-fold contribution: (1) to map potential limitations on feedback thinking in design and (2) to propose pathways to address them. Section 2 presents the background literature with an overview of the engineering origins of feedback. Section 3 contains research methodology. Instances of feedback thought in design science are further described in Section 4. Discussion and conclusions are presented in Sections 5 and 6, respectively.

2. Background literature: the engineering origins of feedback

The engineering origins of feedback thought are discussed by Richardson (1991), who describes the appropriation by social scientists of the engineering concept of feedback, defined as circles of interaction or closed loops of action and information. In addition to offering a historiography of feedback in the social sciences during the 20th century, Richardson (1991) dives into its origins since the Greeks (3rd century BC), who designed the first devices to produce feedback. In the 19th century, a renaissance of servomechanisms (control systems that trigger dynamic responses) emerged in the hands of Watt and other designers of modern feedback machines able to regulate temperature, pressure, and other fundamental physical quantities. Maxwell's mathematical formalization of regulators using differential equations, complemented by Lyapunov and Hurwitz, was an essential step in consolidating this knowledge, which later became accessible with Bode's schematics and generalizations. An absence in Richardson's account is McFarlane Gray's and Farcot's concepts of servomechanism (IEEE, 1996).

Richardson (1991) then narrates the utilization of the construct of feedback (and feedback loop) in describing biological and social systems. In other words, the author implies humans have learned about feedback while trying to build things, and only after that started describing feedback as it exists in non-engineered systems. This notion seems aligned with the early realizations on the science of design (Simon, 1969, chapter 5), describing it as a discipline that devises knowledge first and foremost from creating the artificial or, in other words, from designing or supporting design.

Richardson (1991, p. 143) outlines that Simon started applying the concept of feedback before *The Sciences of the Artificial* (1969). According to Simon (1952, p. 249), a feedback loop is a crucial inventory control system component. Later, it became clear to the pioneer of design science that feedback was a key adaptation mechanism in social systems (Simon, 1954; March and Simon, 1958).

Two main threads of the consideration of feedback in the social sciences are mapped out by Richardson (1991, p. 93): cybernetics and servomechanisms. Six epistemological traditions are listed as origins for both threads: logic, biology-math models, homeostasis studies within biology, econometrics, engineering, and social sciences. Simon is the only author mentioned by Richardson as part of one of the traditions (engineering) and one of the threads (servomechanisms). However, it is not only in Simon that the concept of feedback intersects with the foundations of design science. In this paper, other intersections are hypothesized and demonstrated.

3. Methodology

Figure 1 depicts the research methodological approach. Based on Richardson's framework (1991) - simplified to three epistemological traditions (biology, engineering and economics/econometrics) - a literature review explored how design is treated in the two streams of feedback thought (cybernetics and servomechanisms), with a strong focus on snowballing (Step 1). The original corpus was limited to a pre-determined sample of documents, either because they were cited by Richardson (1991) or identified in a broader review effort in the context of dynamic complexities and unintended consequences.

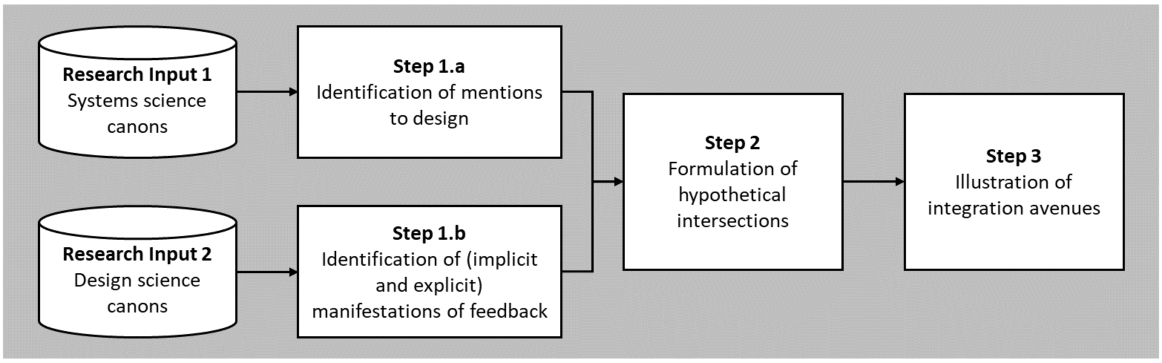

Figure 1. Methodological steps

The potential intersections between the two fields were further investigated by investigating the fundamental consideration of feedback by design pioneers (Step 2), leading to the development of

https://doi.org/10.1017/pds.2024.4 Published online by Cambridge University Press

potential integration avenues (Step 3). From this vantage point, the paper presents a specific study exemplifying the integration of modern feedback principles into design research. Finally, it asserts the necessity of feedback mechanisms in advancing design science, suggesting the next steps for research and application.

Figure 2 details the 59 reviewed documents following Richardson's framework (1991). The left column on each table denotes the analyzed contributions from systems science, and the right column shows contributions from design science. References in the black cell intersect systems and design research. The arrows denote the direction of contributions.

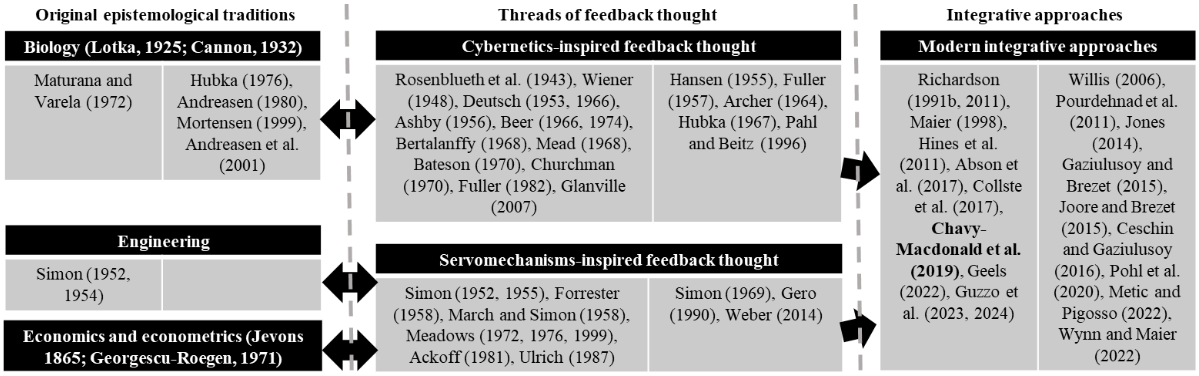

Figure 2. Reviewed literature following an adapted version of Richardson's framework (1991)

4. Feedback thought in design science

The following four sections detail an adaptation of Richardson's (1991) framework to design science. Section 4.1 discusses the feedback-rich biological analogies in design theory, while section 4.2 presents intersections between design and the cybernetics thread of feedback thought. Section 4.3 focuses on manifestations of servomechanisms-inspired feedback thought within design research, including the influence of economic science on this thread. Section 4.4 presents an example of a deeper integration of the possibilities of current feedback computation and design research.

4.1. Feedback-rich biological analogies in design theory

In biology, homeostasis (Cannon, 1932) describes how organisms maintain a stable internal environment based on feedback across organs. Stability is also interrogated at the ecosystem level since Lotka (1925) based on the complex interplay between predators and preys.

In design, Hubka (1976) developed the theory of technical systems, conceptualizing technical artefacts as systems consisting of various 'organs', each responsible for a specific function necessary for the system's operation and stability. In this context, an organ is not a literal biological entity but a set of components designed to perform a particular function within a machine or a device. The idea of feedback is implicitly present both at the organ level (the self-regulation capacity of an organ) and at the systems level (interconnections between organs). Andreasen (1980) took this idea further and proposed the domain theory, which contains interrelated levels of abstraction: the transformation, organ, and parts domains. This view was expanded to comprise multi-level causalities (Mortensen, 1999) and the concepts of modularisation and platform thinking (Andreasen et al., 2001).

In biology, interactions between levels are further articulated by biologists Maturana and Varela (1972) who coined the concept of *autopoiesis* (the self-generative nature of living systems supported by feedback relationships) while also trying to describe the relationships between engineered and living systems, or, in other words between designed and non-designed meaningful sets of interconnected parts. Maturana and Varela also influenced the cybernetic tradition. Contemporary views of cross-scale influence of design can be found in Joore and Brezet (2015), who show that design can intervene at different interconnected levels (product, product-service systems, socio-technical systems, societal systems), as well as in Gaziulusoy and Brezet (2015), who demonstrate the dynamics of global system innovations impacting local operational contexts and vice-versa, both constrained by delays.

https://doi.org/10.1017/pds.2024.4 Published online by Cambridge University Press

4.2. Intersections with the cybernetics thread

Cybernetics is known as the science of feedback. Its first defining work is usually attributed to the mathematician Norbert Wiener (1948), who explained the etymological trick employed by the original cyberneticians to name the field by referring to the classic Greek word *kybernetes* (steersman). This term later evolved into the first occurrence of the word ‘governor’, in the Roman times. This choice of words reveals the cyberneticists’ view of a world governed by feedback. Less known is the earlier work led by a physiologist (Rosenblueth et al., 1943) who pioneered the societal application of the engineering concept of feedback. Since 1941, the Macy conferences on cybernetics have gathered a community of researchers from different disciplines applying the concept of feedback.

In an apparently unrelated endeavour, Hansen (1955), a pioneer of design methods, proposed a systematic approach to design intended to ensure that designers could tackle complex problems by breaking them down into manageable, interrelated parts. Hansen’s systematic design may have seemed to diverge from the cybernetic considerations of his time by adopting a purely reductionist approach.

However, one year later, Ashby’s law of requisite variety (Ashby, 1956) was published. Inspired by Hurwitz’s and Nyquist’s early engineering servomechanics, it is paramount to understanding control systems. For a system to be stable, the number of states of its control mechanism must be greater than or equal to the number of states in the system being controlled. This law suggests that the controller’s complexity must match the system’s complexity to achieve the desired outcomes. It has broad implications for design, suggesting that the design process must incorporate a sufficient variety of responses to deal with the complexity of the system being designed, in line with Hansen (1955) considerations on complexity generated by detail and the need to find key design principles that fulfil the necessary requisite variety. Hansen’s “basic system” incorporates feedback thought in its process dimension (by adding the failure critique step to the design process) and in its analysis and evaluation dimension by applying Ashby’s law to design.

One of the most prominent early cyberneticists was also a designer. Buckminster Fuller’s approach to design was often described as “comprehensive anticipatory design science” (Fuller, 1957), published one year after Ashby’s law. It relies heavily on feedback for both foresight and the iterative design process. By anticipating future needs and environmental changes, Fuller’s designs could adapt over time, providing feedback-informed solutions that were sustainable and comprehensive. Perhaps Fuller’s most notable contribution is the concept of “synergetics”, which describes the cooperative interactions within systems that give rise to complex structures and unexpected behaviours (Fuller, 1982; first edition in 1975). Feedback is critical in this concept, as it is how a system self-regulates and evolves over time. Both Archer (1964) and Pahl and Beitz (1996; first edition in 1977) incorporate the notions of iteration and recursion more deeply when elaborating on Hansen’s systematic approaches to design, considering the need for information feedback within the design process to properly account for such complexity. Recursion is still emphasized in the current literature on the mutual relationship between design and cybernetics, such as in Glanville (2007). Together with participant observation, it became a more prominent topics in cybernetics since the dawn of second-order cybernetics (Mead, 1968), when the field broadened its perspective to incorporate the observer as someone who also contributes to determining input and output. Analogically, a common reference to substantiate reflective practice in design is Schon (1983). The systemic design movement can be considered a modern expression of higher-order cybernetics in design, also based on its proposed expansion of the scope of action of the design profession to incorporate the need for social transformation. Its narrative borrows elements from early cybernetics, such as the definition of purposive systems (Jones, 2014, p. 17).

Hubka’s first depiction of a technical system (1967) follows a basic ontology of systems published one year later by Bertalanffy (1968), composed of input, (system) throughput, output, and system boundaries that distinguish a system from its environment. It is perhaps important to point out that it was only since Churchman (1970; see discussion in Midgley, 2000, p. 36) and Maturana and Varela (1972) that it became clear to cyberneticists that, in the context of the interaction between the engineered and the non-engineered, systems are social constructs which do not require a pre-established purpose to be considered systems (see Midgley 2000, p. 51, for a discussion on Bateson, 1970). That is why the views on subject/object duality and boundary setting in both Wiener (1948) and Bertalanffy (1968) are often described as naïve teleology (Midgley, 2000).

https://doi.org/10.1017/pds.2024.4 Published online by Cambridge University Press

But how could Hubka know of Bertalanffy's basic ontology before the publication of General Systems Theory (1968)? Well, since the 1940s, Bertalanffy had been actively involved in promoting and consolidating such theory, in a process that is described as parallel to the Macy conferences (Richardson, 1991, p. 118), nevertheless ontologically and epistemologically coincidental with cybernetics.

The idea of feedback in Hubka (1967), although persistent in contemporary depictions of feedback in design (e.g., Wynn & Maier, 2022) is very much aligned with the early cybernetic view: it is depicted as an informational link between the output and the input of a system, leading to new (implicit or explicit) goals for the system. These self-regulatory, homeostatic loops are known as negative feedback loops in modern systems science (Richardson, 1991). They were described in the systems-inspired design sciences of the 1960s mostly without the use of mathematically formalized models. In contrast, some of the political science and management applications of cybernetics were already more sophisticated in this regard (see the appendix to the 1966 edition of Deutsch, 1953 and Beer, 1966). Management cyberneticist Stafford Beer writes about design and designed systems (Beer, 1974, p. 42):

> *Some systems adapt to change in a stable way —but only to such changes as they were actually designed to accept. Most engineering systems are of the kind; and if a change affects them that the designer did not foresee, they succumb.*

Beer's statement summarizes the limitations of the intersections between design and the cybernetics thread of feedback thought, especially in the strict sense of systems designed by humans, with bounded consideration of unintended effects arising from interactions with social systems. Indeed, cybernetics-inspired design theory seems to be more concerned the processual aspect of feedback: making design systematically iterative and recursive. The intersections with the servomechanisms thread, presented in the next section, tend to incorporate a more nuanced view of such interactions.

4.3. Intersections with servomechanisms and the influence of economics

The servomechanisms thread of feedback thought does not coincide with the cybernetic in its philosophy of science (Richardson, 1991). Epistemologically, it emphasizes formal mathematical representations of dynamic systems, including explanatory models of non-linear instability in systems, represented by positive feedback loops that drive such systems farther from equilibrium. System boundaries are expanded to include feedback mechanisms, meaning feedback is not treated merely as external linkages from a system's outputs to its inputs but as constituting parts of a system. The servomechanisms thread avoids teleology by adopting complex causal hypotheses to describe reality instead of trying to break down a system from its intended purposes. Decision heuristics are also described mathematically, meaning that the models explicitly state the human linkages with the investigated systems. Such complex causal hypotheses (composed of several variables) that are needed to explain the problematic system behaviour under investigation can be added to the models, regardless of whether these variables can be controlled by the main *designer* of the system or not. Geels (2022) reinforces the need for such complex hypotheses when interrogating socio-technical transitions.

This set of priors is what allows the modern endogenous perspective (Richardson 1991b, 2011), which is increasingly employed in the decision analysis realm when purely input-output or econometric perspectives are not able to explain complex non-linear system behaviour (for example, see Collste et al. 2017). Such endogenous perspective was very much present in the early works of the design pioneer Herbert Simon (1952), who credited the econometrist Richard Goodwin with the fundamental realization that separates the so-called policy models (models that consider existing decision heuristics and their effects) from policy-neutral models (trying to isolate and remove the effects of decisions). Meadows (1976) drew the lines on the different paradigms behind economics, including the fundamental differences between classic input-out, econometrics and complex system dynamics.

Georgescu-Roegen (1971), the founder of ecological economics, argues in favour of complex causation in Economics and policy analysis. He argues that Jevons (1865), one of the founders of the neoclassical movement, was ahead of his time when he described the *Coal Question* in circular (feedback-rich) causal terms. Roegen demonstrates that Jevons's hypothesis, nowadays known as the Jevons paradox, was not seriously evaluated due to the lack of modern physics and mathematics knowledge by the economists of the time. What is not usually noted is the coincidence between the feedback thought in Jevons and

https://doi.org/10.1017/pds.2024.4 Published online by Cambridge University Press

the fact that he analyzed the effects of adopting Watt's steam engine (a servomechanism) on the British economy, causing a non-linear, unsustainable coal consumption growth. Did the machine inspire Jevons to describe its societal effects? Whether or not this was the case, the fact is that he initiated a long-standing conversation on the rebound effects of new technologies and products (Lange et al., 2021).

Another characteristic that allowed the evolution of the servomechanisms thread was the early use of computation, building on early insights by Simon (1955) on the limits of human rationality and the effects of the availability of information and computation. JW Forrester, the founder of the system dynamics methodology, was an early adopter of computer simulation of complex feedback mechanisms, including depictions of decision rules and accumulations as differential equations (since Forrester, 1958). In his early works, Forrester reveals an endogenous perspective of why economic cycles are unintendedly created and amplified, including the possibility of collapse if certain non-linear positive feedback mechanisms dominate. This line of research originated the *Limits to Growth* report (Meadows et al., 1972), which operationalized the Jevons perspective globally, demonstrating that superlinear economic growth inevitably leads to either amplifying oscillations in well-being or a global collapse.

Among key design theorists, Gero incorporates more explicitly the endogenous, feedback-rich and computational aspects of the servomechanisms thread. In his seminal function-behaviour-structure framework (Gero, 1990), he formulates an ontology composed of classes of variables that describe a design object, including feedback loops between them. A computer science professor, he keeps these concepts computable. Moreover, he describes the nature of the processes between these classes, including an evaluation process to compare the system structure's actual behaviour to its expected behaviour in the case of full acceptance of the designed solution.

Another design author who has similar concerns with ontology and computation is Christian Weber. The concept of properties in Weber's characteristics-proprieties modelling and property-driven development frameworks (Weber, 2014) is relatable to Gero's concept of behaviour from structure. The fundamental difference is that Gero admits the possibility of the designer having initial assumptions in terms of expected behaviour (which could be translated to something like expected properties in Weber terms) beyond the idea of characteristics (what is directly controllable by the designer). Gero reckons the designers' ability to hypothesize their creations' uncontrollable effects in line with the endogenous perspective preached by the servomechanism thread of feedback thought (Richardson, 1991). In systems science, this notion is discussed by Ackoff (1981), who developed the concept of idealized design, stimulating collective processes to list desired properties of systems.

Gero's evaluation process can be related to the work of Werner Ulrich, who developed his critical systems heuristics. Ulrich (1987, p. 279) asks questions such as "who ought to be involved as designer of the system" and "where ought the designer seek the guarantee that his design will be implemented and will prove successful, judged by the system's measure of success". In Ulrich's view, these questions should be used to challenge the definition of system boundaries and promote the inclusion of more perspectives in evaluating what a system's success means. A modern expression of this type of boundary critique in design science is the ontological design movement (Willis, 2006). In some of its angles, the systemic design movement (Jones, 2014) also incorporates Ulrich by stimulating the involvement of more stakeholders across all design phases, also building on the concept of wicked problems by Rittel and Webber (1973). Midgley (2000) elaborates on this notion to define systemic intervention as the type of intervention that leads to reflection on the boundaries of a system, creating an additional layer of feedback to Schon's (1983) reflective loop model, which is often mentioned in design.

Building on Meadows (1999), Abson et al. (2017, p. 32) define the design aspect of a system as "the social structures and institutions that manage feedback and parameters", which can be interpreted, in Ulrich terms, as the social structures that define the boundaries of the system. By adding the possibility of setting system boundaries beyond the designed and the engineered, the servomechanism thread expands the consideration of feedback in design.

4.4. Integrative feedback thought for design research

Among many studies simulating innovation-related phenomena with system dynamics modelling, Chavy-Macdonald et al. (2019) is a rare example incorporating design and engineering vocabulary. As shown in Table 1, the authors do not limit themselves to the philosophical assumptions of the one tradition but employ assumptions from the three streams of feedback thought.

Table 1. Ontological and epistemological assumptions of each analyzed thread

	Biological analogies	*Cybernetics-inspired*	*Servomechanism-inspired*
Origin of problems	Lack of self-regulation capability	Lack of information about system outputs; limited iteration	**Interconnected, non-linear nature of systems**
Consideration of feedback	**At internal and ecosystem level**	Exogenous link between output and input	**As part of the systems (endogenous view)**
Nature of complexity	**Interaction of function-driven entities (e.g., 'organs') with context**	**Excessive or lacking detail in engineered systems as compared to requirements**	**Dynamic complexity (causing non-linear behaviour over time)**
Purpose of modelling	**To describe cross-scale relationships**	**To prescribe recursive and iterative processes and devices**	**To support decision making (policy models) and expand mental models**

The authors not only propose to simulate classic R&D and innovation diffusion dynamics, which is common in servo-inspired system dynamics modelling (e.g., Maier, 1998), but also decompose the attractiveness of a product into several part-utilities based on the incorporation of new product functions, adding nuance to the computation of adoption based on design parameters.

This feature of Chavy-Macdonald et al. 2019, using simulation to connect a computation logic close to Gero's (1990) and Weber's (2014) to the innovation diffusion domain (Rogers, 1962; Bass, 1969), allows them to reason about what design properties and characteristics drive adoption of a product at each point in time. This is plausible also due to the advancement of the calibration techniques of multivariate dynamic models, allowing new levels of confidence in such models (e.g. Oliva, 2003). Chavy-Macdonald et al. calibrate their model to explain the diffusion of freezers between the 1960s and the 1980s, using publicly available data.

The same simulation model can be used to generate what-if scenarios representing what could have happened if certain product characteristics had not been made available when they were. This approach could also be used to represent the interconnections across product families, which constitute a central topic in the biologically-inspired modularisation research (Andreasen et al., 2001) within design. Depending on the introduction of characteristics, dynamically testing what-if diffusion and adoption scenarios can be powerful for designers to reason about the societal responses to design.

Another aspect of Chavy-Macdonald et al. (2019) is generic model structures. Among the types of such structures that exist in the simulation modelling realm, the authors chose to use "molecules" (Hines et al., 2011). Molecules are hierarchically-organized sets of differential equations and corresponding visual representations (as stock-and-flow diagrams) which give modellers the possibility of choosing among different levels of disaggregation to recursively represent a certain phenomenon (in the case of Chavy-Macdonald et al. 2019, R&D pipelines and innovation diffusion). Modellers then connect these molecules using a process known as "construction by replacement", which can be considered an expression of modularisation (Andreasen et al., 2001) in systems research. If the idea of modularisation in design favours the consideration of complexity and supports a holistic view, the application of the same concept in systems science may contribute to the agile and effective representation of design phenomena, which can then provide insight into design practice.

5. Discussion: feedback mechanisms in the advancement of design

A narrow definition of "systems" in design research, often limited to the early cybernetics view of purposive systems that defined strict boundaries around the designed and the engineered, is still present in contemporary literature. Not incorporating the idea of systems as social constructs that do not respect the borders between designed and emergent can pose risks to considering unintended consequences of design. In contemporary system science, purpose is treated as an emerging property. Gero (1990) offered an ontological perspective that potentially resolves these paradoxes by incorporating feedback and by positioning the designer as a participant observer.

https://doi.org/10.1017/pds.2024.4 Published online by Cambridge University Press

Chavy-Macdonald et al. (2019) offer a promising pathway toward an integrative view on the topic, reconciling engineering, social and systems sciences via simulation. By treating hierarchies of designed components as such and integrating them into explanatory models of complex societal phenomena, the authors pave the way for computing the artificial within the social and biological. By doing so, there is potential to harness on the power of feedback thought to anticipate potential unintended consequences of design, such as the ones leading to rebound effects (Guzzo et al., 2023; Metic and Pigosso, 2022).

Ex-post simulation of technological transitions (e.g., Chavy-Macdonald et al., 2019) has an important pedagogical and theory-building role. However, the real challenge resides in anticipating the complex societal effects of technology, as observed by Beer (1974) and pioneered by Jevons (1865). Anticipatory simulation depends on the systematic description of such effects and the advancement of modularisation in simulation modelling. The complexity of social and socio-technical systems is dynamic and can not be explained purely by excessive or lack of detail in designed systems. In any case, considering feedback in design seems key to considering counterintuitive effects, such as rebound effects.

6. Conclusion

This paper represents a first step in establishing a research agenda connecting systems and design sciences through the fundamental idea of feedback. Its empirical aspects were limited to applying a previously defined framework (Richardson, 1991) to a pre-defined set of documents and one case of application of modern feedback thought into design (Chavy-Macdonald et al., 2019). A more systematic search of existing literature, with better-defined inclusion criteria, is required to complete the inductive task of connecting the two fields. The future steps of this research project involve representing several design approaches in sociotechnical system models that transcend the boundaries of designed systems.

Design and engineering seem to have been a source of inspiration (about feedback mechanisms) to develop our ways of creating knowledge on social and biological systems, which then feed back into design in the form of meso and micro theory. The Greek and 19th-century designers of feedback machines probably could not imagine such unfolding from their inventions. Research is needed to frame and test this conjecture, potentially via systematic historical research and documental analysis. The role of design in addressing the multiple crises human civilization faces is undeniable. The incorporation of feedback thinking in design theory and practice can enable early identification (and prevention) of unintended consequences of design decisions, such as rebound effects, which might hinder humanity's progress towards sustainability constitute a meaningful domain of application of feedback principles in design. Our future research in creating the building blocks to allow ex-ante simulation of rebound effects will hopefully serve as a foundation for other interfaces between design and systems research.

Acknowledgments

This project is co-funded by the European Union (ERC, REBOUNDLESS, 101043931). Views and opinions expressed are however those of the authors only and do not necessarily reflect those of the European Union or the European Research Council. Neither the EU nor the granting authority can be held responsible for them.

References

Abson, D.J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., Von Wehrden, H., Abernethy, P., Ives, C.D., Jager, N.W. and Lang, D.J., 2017. Leverage points for sustainability transformation. Ambio, 46, pp.30-39. https://doi.org/10.1007/s13280-016-0800-y

Ackoff, RL., 1981. Creating the Corporate Future. Wiley, New York.

Andreasen, M.M., 1980. Syntesemethoder på Systemgrundlag – Bidrag til en Konstruktionsteori. Lund University.

Andreasen, M.M., McAloone, T. and Mortensen, N.H., 2001. Multi-product development – platforms and modularization. A P* insight report. Technical University of Denmark.

Archer, L.B., 1964. Systematic method for designers. Design, pp.56-59.

Ashby, W.R., 1956. An Introduction to Cybernetics. Chapman & Hall.

Bass, F.M., 1969. A new product growth for model consumer durables. Management science, 15(5), pp.215-227.

Bateson, G., 1970. Form, substance and difference. Essential readings in biosemiotics, 501. https://doi.org/10.1287/mnsc.15.5.215

Beer, S., 1966. Decision and Control: The meaning of operational. The meaning of operational research and management cybernetics. Wiley.

Beer, S., 1974. Massey Lectures, Thirteenth Series. Canadian Broadcasting Corporation.
Bertalanffy, L.V., 1968. General system theory: Foundations, development, applications. G. Braziller.
Cannon, W., 1932. The Wisdom of the Body. W. W. Norton.
Ceschin, F., and Gaziulusoy, I., 2016. Evolution of design for sustainability: From product design to design for system innovations and transitions. Design Studies, 47, 118–163. https://doi.org/10.1016/j.destud.2016.09.002
Chavy-MacDonald, M.A., Oizumi, K. and Aoyama, K., 2019. Towards a generalized system dynamics model for product design & adoption. In Transdisciplinary Engineering for Complex Socio-technical Systems (pp. 455-464). IOS Press, https://dx.doi.org/10.3233/ATDE190152
Churchman, C.W., 1970. Operations research as a profession. Management science, 17(2), pp.B-37.
Collste, D., Pedercini, M. and Cornell, S.E., 2017. Policy coherence to achieve the SDGs: using integrated simulation models to assess effective policies. Sustainability science, 12, pp.921-931. https://doi.org/10.1007/s11625-017-0457-x
Deutsch, K.W., 1953. Nationalism and social communication: An inquiry into the foundations of nationality. MIT.
Deutsch, K.W., 1966. Nationalism and social communication: An inquiry into the foundations of nationality. MIT.
Forrester, J.W., 1958. Industrial dynamics: a major breakthrough for decision makers. Harvard business review, 36(4), pp.37-66.
Fuller, R.B., 1957. A comprehensive anticipatory design science. Royal Architectural Institute of Canada, 34(8), pp.357-61.
Fuller, R.B., 1982. Synergetics: explorations in the geometry of thinking. Estate of R. Buckminster Fuller.
Gaziulusoy, A.I., and Brezet, H., 2015. Design for system innovations and transitions: A conceptual framework integrating insights from sustainablity science and theories of system innovations and transitions. Journal of Cleaner Production, 108, 558–568. https://doi.org/10.1016/j.jclepro.2015.06.066
Geels, F.W., 2022. Causality and explanation in socio-technical transitions research: Mobilising epistemological insights from the wider social sciences. Research policy, 51(6), 104537. https://doi.org/10.1016/j.respol.2022.104537
Georgescu-Roegen, N., 1971. The entropy law and the economic process. Harvard University Press.
Gero, J.S., 1990. Design prototypes: a knowledge representation schema for design. AI magazine, 11(4), pp.26-26. https://doi.org/10.1609/aimag.v11i4.854
Glanville, R., 2007. Try again. Fail again. Fail better: The cybernetics in design and the design in cybernetics. Kybernetes, 36(9/10), 1173-1206. https://doi.org/10.1108/03684920710827238
Guzzo, D., Walrave, B. and Pigosso, D.C., 2023. Unveiling the dynamic complexity of rebound effects in sustainability transitions: Towards a system's perspective. Journal of Cleaner Production, p.137003. https://doi.org/10.1016/j.jclepro.2023.137003
Guzzo, D., Walrave, B., Videira, N., Oliveira, I.C., and Pigosso, D.C., 2024. Towards a systemic view on rebound effects: Modelling the feedback loops of rebound mechanisms. Ecological Economics, 217, 108050. https://doi.org/10.1016/j.ecolecon.2023.108050
Hansen, F., 1955. KONSTRUKTIONSSYSTEMATIK. Verlag Technik.
Hines, J., Malone, T., Gonçalves, P., Herman, G., Quimby, J., Murphy-Hoye, M., Rice, J., Patten, J. and Ishii, H., 2011. Construction by replacement: a new approach to simulation modeling. System Dynamics Review, 27(1), pp.64-90. https://doi.org/10.1002/sdr.437
Hubka, V., 1967. Der grundlegende Algorithmus für die Lösung von Konstruktionsaufgaben. Internationales Wissenschaftliches Kolloquium der Technischen Hochschule Ilmenau, pp.69–74.
Hubka, V., 1976. Darstellung beim Konstruieren. Theorie der Konstruktionsprozesse: Analyse der Konstruktionstätigkeit, pp.125-143.
IEEE, 1996. Origins of the Servo-Motor. *IEEE Industry Applications Magazine*, vol. 2, no. 2, pp. 74-, March-April 1996, https://dx.doi.org/10.1109/MIA.1996.485765
Jevons, W.S., 1865. The Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines. Macmillan & Co.
Jones, P.H., 2014. Systemic design principles for complex social systems. Social systems and design, pp.91-128. https://doi.org/10.1007/978-4-431-54478-4_4
Joore, P., and Brezet, H., 2015. A Multilevel Design Model: The mutual relationship between product-service system development and societal change processes. Journal of Cleaner Production, 97, 92–105. https://doi.org/10.1016/j.jclepro.2014.06.043
Lange, S., Kern, F., Peuckert, J. and Santarius, T., 2021. The Jevons paradox unravelled: A multi-level typology of rebound effects and mechanisms. Energy Research & Social Science, 74, p.101982. https://doi.org/10.1016/j.erss.2021.101982
Lotka, A.J., 1925. Elements of physical biology. Williams & Wilkins.
Maier, F.H., 1998. New product diffusion models in innovation management—a system dynamics perspective. System Dynamics Review, 14(4), pp.285-308. https://doi.org/10.1002/(SICI)1099-1727(199824) 14:4%3C285::AID-SDR153%3E3.0.CO;2-F

March, J.G. and Simon, H.A., 1958. Organizations. John Wiley & Sons.
Maturana, H. and Varela, F., 1972. De máquinas y seres vivos. Editorial Universitaria.
McFralane Gray, J., 1864. Arithmetic of Building Societies. Virtue Brothers & Co.
Mead, M., 1968. The Cybernetics of Cybernetics. In Purposive Systems, edited by Heinz von Foerster, John D. White, Larry J. Peterson and John K. Russell. Spartan Books.
Meadows, D.H., Meadows, D.L., Randers, J. and Behrens III, W.W., 1972. The limits to growth. Club of Rome.
Meadows, D.H., 1976. The Unavoidable A Priori. International System Dynamics Conference.
Meadows, D.H, 1999. Leverage points. Places to Intervene in a System, 19, p.28.
Metic, J. and Pigosso, D.C., 2022. Research avenues for uncovering the rebound effects of the circular economy: A systematic literature review. Journal of Cleaner Production, p.133133. https://doi.org/10.1016/j.ecolecon.2023.108050
Midgley, G., 2000. Systemic intervention (pp. 113-133). Springer.
Mortensen, N.H., 1999. Design Modelling in a Designer's Workbench: Contribution to a Design Language. Technical University of Denmark.
Oliva, R., 2003. Model calibration as a testing strategy for system dynamics models. European Journal of Operational Research, 151(3), pp.552-568. https://doi.org/10.1016/S0377-2217(02)00622-7
Pahl, G. and Beitz, W., 1996. Engineering design: a systematic approach. Springer-Verlag.
Pohl, C., Pearce, B., Mader, M., Senn, L., and Krütli, P., 2020. Integrating systems and design thinking in transdisciplinary case studies. Gaia, 29(4), 258–266. https://doi.org/10.14512/GAIA.29.4.11
Pourdehnad, J., Wexler, E.R., and Wilson, D.V., 2011. Systems & design thinking: A conceptual framework for their integration. Proceedings of the 55th Annual Meeting of the ISSS - 2011.
Richardson, G.P., 1991. Feedback thought in social science and systems theory. University of Pennsylvania.
Richardson, G.P., 1991b. System dynamics: Simulation for policy analysis from a feedback perspective. In Qualitative simulation modeling and analysis (pp. 144-169). New York, NY: Springer New York.
Richardson, G.P., 2011. Reflections on the foundations of system dynamics. System dynamics review, 27(3), pp.219-243. https://doi.org/10.1002/sdr.462
Rittel, H.W. and Webber, M.M., 1973. Dilemmas in a general theory of planning. Policy sciences, 4(2), pp.155-169.
Rogers, E.M., 1962. Diffusion of innovations. Free Press.
Rosenblueth, A., Wiener, N. and Bigelow, J., 1943. Behavior, purpose and teleology. Philosophy of science, 10(1), pp.18-24.
Schon, D., 1983. Becoming a reflective practitioner. How professionals think in action. London: Temple Smith.
Simon, H.A., 1952. On the application of servomechanism theory in the study of production control. Econometrica: Journal of the Econometric Society, pp.247-268.
Simon, H.A., 1954, Some Strategic Considerations in the Construction of Social Science Models. In P. Lazarsfeld, ed., Mathematical Thinking in the Social Sciences. Free Press.
Simon, H.A., 1955. A behavioral model of rational choice. The quarterly journal of economics, pp.99-118.
Simon, H.A., 1969. The sciences of the artificial. MIT press.
Ulrich, W., 1987. Critical heuristics of social systems design. European Journal of Operational Research, 31(3), pp.276-283. https://doi.org/10.1016/0377-2217(87)90036-1
Weber, C., 2014. Modelling products and product development based on characteristics and properties. In An anthology of theories and models of design: philosophy, approaches and empirical explorations (pp. 327-352). London: Springer London.
Wiener, N., 1948. Cybernetics. Scientific American, 179(5), pp.14-19.
Willis, A.M., 2006. Ontological designing. Design philosophy papers, 4(2), pp.69-92. https://doi.org/10.2752/144871306X13966268131514
Wynn, D.C., and Maier, A.M. (2022). Feedback systems in the design and development process. Research in Engineering Design, 33(3), 273-306. https://doi.org/10.1007/s00163-022-00386-z