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The Meta Holonic Management Tree: review, steps, and roadmap to industrial Cybernetics 5.0

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Abstract

Industry 4.0 and 5.0 are currently pushing towards a reconciliation between humans and the concurrent evolution of cyber-physical systems of systems. This constitutes an increasingly complex battlefield in which management and engineering are experiencing hard times. The cybernetics framework, in its recent evolutions, should be refocused to recover a unifying edifice to these challenges. The Cybernetics 5.0, here proposed, aims at finding ways to deal with the complexity of control and management of pervasive networks of digital, analog, mechanic, and human-centered systems. These challenges had always been the basis of cybernetics, but they have been overshadowed by the impressive and exponentially fast advances in information and communication technologies, intelligent automation, and artificial intelligence. However, cybernetics is still crucial when engineering solutions need to move beyond the frontiers of the hard sciences for soft problems, and towards increased interdisciplinarity for hard problems. In this context, holonic architectures are seen as a valuable ground. Hence, holonic foundations are here perfected for the Cybernetics 5.0 vision. The Meta Holonic Management Tree is accordingly proposed as a first methodological instance and factual bridge between cybernetics and the complexities of Industry 4.0 and 5.0.

Keywords Industry 5.0 · Cyber-physical human systems · Cybernetics · Holonic approaches

Introduction

Among the major challenges of this information era, the Industry 4.0 (I40) is one of the most notable, due to its impact in workplaces and turnover in Europe and beyond. Country-wise definitions for initiatives similar to I40 are found for example in Leitão et al. (2020). The term Industrie 4.0 was first used at the Hannover fair in 2011.

Since then, the I40 efforts from worldwide communities have evolved to embrace a new central role for the human actor and related sustainability issues. This effort have recently materialized into a the new concurrent vision of Industry 5.0 (I50) that keeps values, ethics, and overall sustainability into the transformation of the 4th industrial revolution (Ivanov, 2023; Longo et al., 2020; Nahavandi, 2019; Yao et al., 2024). The opportunity of the separation of concerns between I40 and I50 can be misleading in focusing the right overarching vision. In this paper, we will participate to the prudence of Xu et al. (2021) in the debatable introduction of new definitions that risk to distract from achieving practical and viable results. A strategic management of the

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transformation needed by the Industry 5.0 is still undergoing (Ghobakhloo et al., 2023; Leng et al., 2022).

In the following, I50 is meant as an integral conveyor of the new issues that impinges with a greater focus on the human centrality, though grounded in the still active problems of the I40. This choice was made here so as to act simultaneously and holistically in both I40 and I50. As a matter of fact, the works and standards in the automation for industry are seriously taking into account a change of perspective that essentially calls in a new generation of patterns of collaboration and operations between humans and machines. With independent analyses (Leitão et al., 2020; Muhuri et al., 2019; Singh et al., 2024) it is concluded that the two most important concepts and technologies for I40 are the cyber-physical systems (CPS) and the IoT (Internet of Things, along with the principles of their real-time capabilities, optimization, decentralization and interoperability). The CPS concept carries within artificial intelligence (AI) that can be assigned primarily to the *cyber* part of the CPS. This is probably the major requisite that challenges more than ever the pursuing of the CPS principles. Later extensions to the concept of CPS include a renewed and enlarged systemic view for CPS that considers the multiple dimensions of current reference architectures in I40 (Zhang et al., 2022; Leitão et al., 2022). A new element in this play is the digital twin (DT). DT bridges the virtual cyberspace with the physical entities and, as such, is considered to be a pillar and, currently, a backbone of Industry 4.0 (Jiang et al., 2021). Liu et al. (2024) establish a reference model for Digital Twin-based manufacturing system, which is becoming a prominent concept in the digital transformation of manufacturing systems. DT allows digitizing the data and information during the whole product lifecycle, which upgrades the CPS concept to the overarching Industrial CPS (ICPS) framework. ICPSs take into account the role of DTs for the distributed CPS in current industrial practice. ICPSs originate from engineering fields and focus on the applicability and modelling of physical systems, usually in a closed-loop manner, in which the use of MAS (Multi-Agent Systems) is the means to enforce the distributed intelligence of ICPSs and to promote system flexibility, adaptability, and reconfigurability. In addition, ICPSs can be designed based on the holonic principles here addressed, where the complex system can be modelled, managed, and controlled as hierarchical systems with intermediate stable forms (Zhang et al., 2022).

A new concept is also appearing when the ethics and new dimensions have to be added to the design of the CPS. In particular the CPHS (cyber-physical human systems) are object of keen studies and developments in order to render explicit the components in the management and control of systems, whether they involve human agents or artefacts (Valette et al., 2023; Trentesaux & Karnouskos, 2022; Berrah et al., 2021; Salamanca et al., 2022). According to other interpretations, the CPHS can be seen as a goal-seeking socio-technical organism in which problems occur in a new terrain that blends human and artificial cognitive abilities (Yao et al., 2024). Hasbach & Witte (2021) deemed this problematic new world the *homo machina*. Other authors from systems dynamics and system thinking ground have identified this terroir with a new definition of a still unknowable and uncontrollable problem of hybrid reality (Perko, 2020). Other studies sees the very same problem in the intelligent manufacturing system (Habib et al., 2019), which surely requires new detailed studies and design criteria for the context-dependent role exchange between humans and AI as covered by Abbass (2019). Part of the literature introduces the concept of Human Digital Twin (HDT) in DTs to complement CPS to realize the centrality of humans in smart manufacturing systems toward I50, as digital representations of the coupling of human characteristics directly to system design and performance (Wang et al., 2024).

Socio-technical systems theory and systems thinking focus on the importance of social and technical factors for which a change in one part of the system will result in changes in the other parts, but with no easily traceable causality. According to Sony and Naik (2020), to optimize and control all the parts of the systems they should be considered together, in particular in the I40 that features technologies such as smart products, smart machines and smart operators.

Smart operators play a major role in the new industrial revolution, where flexibility must regain the level before the first industrial revolution, when production came out of art and craftamnship and was centralized in factory shopfloors. (Drath & Horch, 2014). An account of this problem has led to the study and definition of a new humans role, namely the *Operator 4.0/5.0* (Romero et al., 2016, 2020; Gladysz et al., 2023; Mourtzis et al., 2022; Rossi et al., 2023; Nguyen Ngoc et al., 2022). Interestingly enough, these visions have today crossed the border of manufacturing to integrate other kind of industries like the construction sector (Yitmen et al., 2023), which in turn provide back to manufacturing new complexities in the dimensions and lessons learnt in human and machine interaction.

As studied by Bonci et al. (2019b) three major incoming trends have been moulding the challenges of I40:

- the first trend is a slow but inexorable crumbling of the ISA 95 or IEC 62264-1 hierarchies into a more distributed and granular specification of the domains and their operational models, more compliant with self-organizing intelligent automation solutions based on evolving aggregates of autonomous entities;
- the second big trend is one in which the whole business is seen as a living being, capable of cognition, autopoiesis, autogenesis and teleology;

- a third trend is the ascertaining of complexity of processes and of the central role of human beings in their seamless and ergonomic collaboration with new intelligent automation means.

These trends have resulted in new definitions like the Cyber-Physical Enterprise (CPE), which consists of autonomous and cooperative technical elements, humans and sub-organisations are across all the levels from processes, through machines and up to enterprises and supply-chains networks (Ali et al., 2024). The new complexity of CPE needs in turn the concept of CCPS (Cognitive Cyber-physical Systems) and of Cognitive Digital Twins (CDT). CCPS applications cover areas such as human-robot synergy, transportation system optimisation, advanced industrial process automation, precision healthcare, and smart agriculture; CDT adds capabilities to an industrial system, by representing the virtual replica of a cognitive entity or process or adding cognitive abilities to it (Ali et al., 2024; Gaffinet et al., 2023). As CCPSs are the cognitive evolution of CPSs, so the CDT is the cognitive version of DT. El Kalach et al. (2024) define cognitive manufacturing as a distinct research domain aiming to reach a level of intelligence that can allow manufacturing systems to keep up with the ever-changing markets and intricate supply chains. Cognition is an upgrade from autonomous faults correction (i.e., autonomic capabilities) towards a system that can “understand” causes of faults and model them for prediction and prevention by prescriptions.

In the previously depicted scenario, research and practice seem to have come up to the point of facing the hard problem of solving or dampening complexity at the many levels of intelligent automation: computing power, interoperability of the technologies, introduction of artificial intelligence (in its general version), proficiency in the collaboration and symbiosis between machines and humans, and overall sustainability. This generates the following three research questions that we are going to address in part with this work:

RQ1 : can a modernized version of trans-disciplinary cybernetics be a valuable weapon for I40/I50 against the increased difficulties of designing and controlling the complex socio-technical playground of current and future industrial activities?

RQ2 : can the promising holonic architectures framework be enriched and reshaped in order to comply with renovated cybernetics principles and visions?

RQ3 : is there a technology and technique available that can be used to demonstrate the effectiveness of the envisioned coupling of holonics and cybernetics for real problems?

RQ1 will be answered with the proposition of a framework that we will deem as *Cybernetics 5.0*. It will be mainly based on a reunion of modern cybernetics and current research in the operational and the informational management technologies of the I40 as a transdisciplinary whole.

Section “Complexity management, intelligence: perspectives from cybernetics” starts with a review of the cybernetics essentials and makes a relation with the problem of complexity of management and control, and finally proposes a definition and a vision for the *Cybernetics 5.0*. In “Cyber-physical systems of systems and perspectives for HMT” section, the holonic approaches are reviewed and author’s HMT (holonic management tree) technique is proposed as a good representative among the holonic architectures available for its strong adherence to the research scenarios of interest. HMT is used to address the RQ2. The HMT, and related methodology, would be in this case only a first tentative and instance for a simple enforcement of the renewed link between cybernetics and the management problems involving CPS for I40/I50.

To answer RQ3, an upgrade of the HMT is needed. It will consist in a systematic meta process that fulfills all the technical and technological requirements of the *Cybernetics 5.0*. A new position of the MHMT (meta HMT) is achieved in “The MHMT methodology against complexity” section. In that section, the new problem at hand will be the first complete definition of a systematic process that handles the meta level, concerning the refinement and synthesis of the HMT, during complex evolutions of the reality that the HMT methodology, as an overall, aims to manage. This framework will be deemed here for the first time MHMT (meta HMT). Many alternatives solutions to the same MHMT problem are of course possible and should be matter of future research by interested communities. This paper will merely briefly present the MHMT and related ongoing research as a means of exemplifying the role of cybernetics for I40/I50.

In “Related work and discussion” section a discussion is conducted to assess strength and limits for future activities, in order to develop a clear research path over a tentative roadmap. Section “Conclusion” is devoted to conclusions.

Complexity management, intelligence: perspectives from Cybernetics

The birth of cybernetics as a discipline can be traced back to 1940, a few years before Norbert Wiener (Wiener, 1948) fathered this name to the area of study of a group of eminent scholars who participated in annual interdisciplinary symposia in New York (the Josia Macy Jr. Foundation conferences). The subject of this interdisciplinary group of scholars was “Circular Causal and Feedback Mechanisms in Biological and Social Systems” (Von Foerster , 2003b). Among other eminent scholars, John von Neumann, Warren Mc Cullock, and Walter Pitts were members in this group. Subsequently, it was thanks to Von Foerster's proposal that the name of the conference was shortened into "Cybernetics" (Von Foerster, 2003c), with an emotion from Wiener receiving such a lovely acknowledgement from the group.

The core of this discipline was synthesized well by Von Foerster himself in this passage: "*My suggestion is that we apply the competences gained in the hard sciences – and not the method of reduction – to the solution of the hard problems in the soft sciences. [...] it is precisely Cybernetics that interfaces hard competence with the hard problems of the soft sciences. [...] and today "Cybernetics" has ultimately come to stand for the science of regulation in the most general sense.*" (Von Foerster, 2003e).

A famous joke from Stafford Beer reminds us how difficult today is to is to deliver a final and definitive answer to the question: "what is cybernetics?". [1] Since then, this discipline has grown in many directions and now encompasses a broad set of scholars and disciplines ranging from humanities to physics, to cover systems engineering as a management technology based on information science.

It was precisely the contrast between the holistic and the reductionist worldviews that gave rise to the chasm between the disciplines of control and systems engineering and computer science. This is where cybernetics began to lose its primacy in the science of the artificial during the 1950 s. Thanks to Malapi-Nelson (2015), we have a detailed account about the motivations that brought to the fading of cybernetics during the last 70 years. In particular, it is rather clear that the success of the Von Neumann's architecture for information processing has seized some scenes to the more complex and complete sciences of the artificial (Simon, 1996). This historical event has been implying a dominant direction and trend in research, technology, and innovation – namely, the Big Science – that typically proceeds from the bottom of technical practice and brute force approaches up to affect scientific inquiry in most cases. It can be observed that this is a common pattern, occurred many times in the history of technology: the cybernetic principle of self-regulation was anticipated by the governor of J. Watt a century before cybernetics itself (Malapi-Nelson, 2015; Masani, 1994); quantum-mechanics effects have been used proficiently since the transistors' birth, but no unified theory of quantum mechanics exists so far after a century to provide a scientific explanation (Rovelli, 1996, 2021); model predictive control is an engineering reality in industry, which comprehensive theoretical and formal model is still not achieved (Pathak & Prasad, 2015); and so on. It is indeed important to focus on the fundamental role of engineering for progress as "sometimes engineering does precede science rather than the other way around" (Lee, 2017). The "linear" model of innovation, which holds that scientific discovery leads to technology, simply has not being tenable most of the time (Macilwain, 2010).

The recent progress of technology and industrial production has been mostly a result of excellent craftsmanship of engineers and practitioners, rather than scientific breakthroughs.

Definitely, the chasm between computer science and holistic and systemic approaches like cybernetics took its great advantage due the very first principle for engineers: to avoid complexity. Von Foerster (2003e) expressed this dominating engineering stance very clearly in his *theorem number one*: "*The more profound the problem that is ignored, the greater are the chances for fame and success.*". Today, complexity re-enters the front door of industrial practice and can no longer be ignored or avoided nor addressed with the usual specialized approaches (Pirani et al., 2021; Leng et al., 2022).

Complexity knocks at the Industry 4.0 door, who is to open?

What is the generator of complexity in industry? The quick answer is, the industry itself. But the second answer is *time*. The onset of complexity is caused in general by lack of resources in order to solve a problem. Time is a special resource, so special that we cannot completely consider it as such (Lee, 2009). While we can optimize resources for some problems, time cannot be controlled in this sense: time gets expended whether we use it or not and cannot be conserved and saved for later.

Some analyses in decision-making field like Badinelli et al. (2012) reveal that complexity lies in the eyes of the observer: different observers perceive a different level of complexity; the complexity that individuals attribute to a specific situation varies depending on their knowledge; a system is not simplex or complex in itself. An elucidating example authors make in Badinelli et al. (2012) is the Rubik's cube problem. The Rubik's cube structure is not complex in itself. By simply rotating the pieces of the cube in a random fashion the solution is always reachable, allowing an indefinite amount of time available. Indeed, it is time scarcity at the very origin of complexity, in particular when we confront complexity with complicatedness.

Irene Ng provides a nice general account of the difference between complex and complicated (Ng, 2011). It is noted that we have spent the last 100 years doing complicated things rather well, "we can pat our backs on putting the man on the moon, doing brain surgeries etc.". To transform complexity into complicatedness, traditional science and engineering has taught us to reduce everything and then put them the pieces together to get the outcomes we want – as if we could always count on *trivial machine* behaviors according to Von Foerster (2003d). According to Beale et al. (2023) (and references

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[1] https://asc-cybernetics.org/definitions/

therein), the systems engineering (SE) community currently agrees on the following definitions:

- A **complicated system** has elements, the relationship between the states of which can be unfolded and comprehended, leading to sufficient certainty between cause and effect.
- A **complex system** has elements, the relationship between the states of which are weaved together so that they are not fully comprehended, leading to insufficient certainty between cause and effect.

In complex systems the outcome of an action or design can only be incentivised but not guaranteed or determined (Haugen et al., 2023).

Generally, is time (scarcity) that causes non-determinism and emergence. The decision maker (human or automaton) is confronted with the adoption of fast-and-frugal heuristics (Hafenbrädl et al., 2016), with usually trading off optimality for adaptation (Baumann & Siggelkow, 2013). It is impossible to optimize in the real world; and decision making relies on models of bounded rationality that are geared toward *satisficing* solutions that barely suffice to satisfy the decision maker's goals (Simon, 1996).

Wherefore, complexity requires to look elsewhere, in holistic way, while keeping the systemic details into due account (Von Bertalanffy, 1972). Here dwells the relation between intelligent decision making and cybernetics, in particular in relation to modern acceptations of cybernetics, as detailed further in the next section. For the moment, it suffices to note that for the goals of industrial production, time itself is not a free variable in the problem, but is in turn controlled and determined by production targets.

Prima facie, there is an obvious causal connection between the desired augmented performance of production and the shortening of process timings. It has always been like this, since the second industrial revolution. Now, it is even stronger in the coupling between the I50 and innovative management processes. The connection between complexity, time, and expected performance can be easily framed into a context-based constructivism in which the reality of time depends on the active intervention of the observer. Reflections about time have been permeating hard sciences like physics for more than a century – see for example locality of quantum events and space-time effects in Rovelli (2021).

Complexity becomes apparent with the continuous search for improvements in the capacity and efficiency of production systems. New design and management sciences and methodologies have been dealing with this type of problem for a long time now. Today, the inter-discipline of systems engineering (SE) is trying to create a meeting and a moment on these kinds of aspects as well (Kossiakoff et al., 2020; Haugen et al., 2023). The focus in I40 is still, as an overall, in the continuous improvement of performance by means of systemic lean and agile approaches (Ding et al., 2023; Rossini et al., 2019; Gunasekaran et al., 2019).

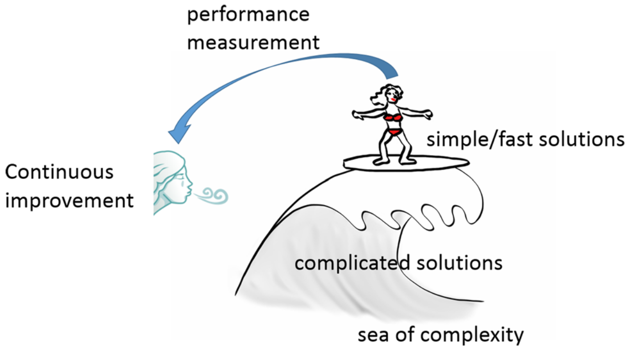

Fig. 1 Cybernetician's worldview of performance improvement in complex production systems

In (Ravelomanantsoa et al., 2019), 60 performance measurement systems are surveyed, all contributing in different ways to overall improvements. The success of a methodology depends on the specific case, constraints and needs. In addition, a suitable meta-development and design is needed in order to render any of the performance measurement methodology effective Moura et al. (2023). These methods are essential modelling elements of the cybernetic control loop that is always enforced (more or less implicitly) in the problem of continuous improvement of production, both in efficiency and sustainability dimensions.

Hence, a cybernetics worldview of the complex production improvement can be metaphorically shown with Fig. 1.

This figure depicts a metaphor of a complex production system seen as the *sea of complexity*. In this sea, due to the impending waves, complicated and heavy solutions – that consume too much time – cannot take the pace of the waves and are doomed to inescapable swamping. The only way out is trying to stay on the crest of the wave, with light, fast, and simple solutions. When this state of system organization is achieved, performance measurement provides feedback to decision makers. But decision makers blow on the sea in order to obtain continuous improvement, and this provokes the waves. It is an open dynamical equilibrium of a relentless circular process. The awareness of this cause-effect loop provides a cybernetics vision that would help escaping social and economic disasters at the many complex dimensions of production systems.

With the identification of this cybernetic model, multi-objective solutions covering social, sustainability, and economical aspects can be focused and tackled in the appropriate manner—for example, why we keep blowing so strong on the waves, in the first place.

In recent research and developments, a possibility for a step change in the field of control and management of cyber-physical systems of systems (CPSoS) seems to come from a path that is worth being explored in more depth (Bonci et al., 2018a, b; Bonci et al., 2018c). This path has eventually been found impinging on the themes of cybernetics, a discipline that acknowledges the importance of the circularity and inherent recursiveness of the application of control loops at different semantic levels of reality (state of affairs) (Raikov & Pirani, 2022b). This property can be a key for the adoption of a methodology that simplifies the modelling and then the control of systems of systems (SoS) occurring and emerging everywhere in I40 and I50.

Cybernetics 5.0: teleology of production management and control

The core of cybernetics is usually traced back to a fundamental work of Rosenblueth, Wiener, and Bigelow (Rosenblueth et al., 1943) aiming at classifying behaviours of systems and the concept of purpose. Purposeful behaviours require negative feed-back, and purposeful active behaviour may be essentially subdivided into two classes: "feed-back" (or "teleological") and "non-feed-back" (or "non-teleological"). Production systems associated to purposeful processes in I40 have necessarily to be teleological, in order to actively pursuing targets that are not stationary. Giunchiglia & Fumagalli (2017) resort to the concept of teleology to tackle the problem of formalizable connection between different levels of knowledge, proceeding from an object of physical realm up to its behaviour and function.

The other sought-after feature of interest for production systems is their being predictive at different orders. For the discussion that will follow, it is postulated that a production process, in the I50 context, has to feature the following characteristics:

1. *active behaviour*, as the system produces outputs in the environment that cannot be directly (or trivially) related to the inputs received;
2. *purposeful behaviour*, in order for the systems to be interpreted as directed to a goal;
3. *teleological behaviour*, meaning that a negative feed-back circuit is active in order to let the purpose be reached against disturbances or non stationarity of the goal; teleology implies an agent (or a controller) that senses through its receptors and actuates through its effectors after a "brain" has interpreted signals and then decided which commands should be issued to reach the purpose (Masani, 1994);
4. *predictive behaviour*, at different orders, in order to direct and adapt or "reprogram" the teleological mechanisms.

In Rosenblueth et al. (1943), the manifestation of predictive behavior implies necessarily all the others. Another important statement from the authors is that animal (organisms), nature, and machines are prone to this very unifying classification.

A peculiar aspect of cybernetics is the view of the world as composed of machines by extending the notion of *machine*, in the words of W. Ross Ashby (Ross Ashby, 1968): "[A] *machine is that* [whose] *internal state, and the state of its surroundings, defines uniquely the next state it will go to*".

This definition is unifying between computer science, automata theory, and the discipline of control and systems engineering, due to the implicit adoption of a state space. Moreover, this definition in no way requires a mechanistic and materialistic position. It only implies that it is possible to adopt cybernetics as an overarching (and new) scientific stance.

Since its inception, cybernetics evolved to become a viable methodology for the introduction of engineering into any kind of systematic process, system, or natural phenomena. Nowadays, cybernetics offers a relational reflexive epistemology in which the knower is responsible for their meaning-making, values, and ethics (Chapman, 2019). A taxonomy of cybernetics can today be performed to arrive to the definition of a third order cybernetics (Lepskiy, 2018), which can currently be paralleled to the evolution of artificial intelligence (AI) (Raikov, 2019; Raikov & Pirani, 2022a, b).

A summary of the cybernetics evolutions can be provided as follows.

- 0-*th order cybernetics*. The case in which cybernetics is implicit and the purpose is not defined nor identifiable. An activity gets a structure and behavior can emerge, but no interpretation or motivation is available (Von Foerster, 2003c). This corresponds to a mechanistic and materialistic philosophy and worldview.
- 1-*st order cybernetics*. The cybernetics of observed systems. This is when one reflects upon one's behavior, upon the "how" and the "why". Then cybernetics becomes explicit through the notions of feedback, information, circularity, recursion, control, homeostasis, dynamic stability, fixed points, attractors, purpose, and goal (Von Foerster, 2003c). This corresponds to the classical type of scientific rationality, concentrating attention on the object of reality, in theoretical descriptions and explanations, but tends to eliminate everything that refers to the observer and means and operations of scientific activity (Lepskiy, 2018). This is also the original Cybernetics science about the general regularities of control processes and information transfers in mechanisms, live organisms, and society (Wiener, 1948; Ross Ashby, 1956).
- 2-*nd order cybernetics*. The cybernetics of observing systems, in which the observer enters the system by stipu-

lating his own purpose (Von Foerster, 2003a). Is a concept that corresponds to non-classical scientific rationality based on an external observer. In second-order cybernetics, the observer is built-in and integrated into the control object (Lepskiy, 2018). This vision is also aligned with philosophical constructivism and second-order science (Umpleby, 2014).

- 3-*rd order cybernetics*. The cybernetics of self-developing reflexive-active environments (Lepskiy, 2018). In this case reality is in a close and entangled relation between the observed object, the observer, and the environment in which the observer is immersed. The environment is active and reflexive with respect to the phenomena and determines the current status of the observer and of the observable at the same time. This corresponds to a post-non-classical type of rationality that broadens the field of reflexion on scientific activity, which means the connection of inner-scientific goals with extra-scientific ones and social values (Lepskiy, 2018). This framework opens new directions and challenges in the science and technology of artificial intelligence (Raikov, 2019; Raikov & Pirani, 2022a, b).

There exist alternative definitions of 3-*rd order cybernetics*, for example in the Eric Schwarz's third-order cybernetics as treated by Raikov and Pirani (2022a). Higher orders of cybernetics have been envisioned by authors like Ashby (2020, 2022), Yolles (2021), and Yolles and Fink (2015) but their adoption are still too far reaching being the current status of the practical short-term developments in I50.

However, I50 is already about the application of advanced technologies to manufacturing as a "whole" (Xu et al., 2018). It is clear also to practitioners that the digital transition and the progresses in ICT (information and communications technology) of the last decades are not providing all the solutions by themselves, because the role of humans and their societies is going to be central in the future and inseparable from the goals and strategies of industry (Ivanov, 2023; Yitmen et al., 2023). Now the biggest trend is on sustainability as a whole, which involves humans at the center (Gladysz et al., 2023; Mourtzis et al., 2022; Nguyen Ngoc et al., 2022; Rauch et al., 2020; Romero et al., 2016, 2020; Yao et al., 2024) and the ecological approach in wide sense—a vision sometimes attributed to the I50 (Breque et al., 2021; Leng et al., 2022).

As observed in Malapi-Nelson (2015) and previously discussed, cybernetics in recent years has more been focused in the "soft" part of reality, concerning more the management and social interactions, with a pronounced detachment from engineering problems to better attack problem in complexity and general systems theory (Umpleby et al., 2019). Currently the gap between systems science, systems theory, and systems engineering is still in search of an effective solution and harmonization (Keating et al., 2020). Third-order cybernetics can be an effective framework in this regard insofar, as the domain of interest returns to engineering but with a renewed transdisciplinary and multifaceted vision (Nicolescu, 2014; Wang & Tunstel, 2019).

The *Cybernetics 5.0* here proposed aims to denote such a return of the last evolution of cybernetics into the realm of the overwhelming complexities that appear in the I40, I50, and related concepts. The definition of Cybernetics 5.0 provides foundational integration of recent approaches based on system of systems that allow a holistic orientation of the engineering, control, and management of industrial processes. According to Simões (2024): "Cybernetics, which was a theory of everything, inverted from the inside out to become an everything through a theory, an interplay of technology, society, and the environment, approaching complex systems through processes like feedback and communication, engineering systems, and systems engineering."

Cybernetics 5.0 goes in parallel with Industry 5.0 by name. It focuses sustainability as a whole, of which ethical, economical, societal, and environmental issues are the "soft" part of the system, but ready to be faced with "hard" science and engineering tools. Industry 5.0 is reintroducing human and natural components in the system. These factors re-connect the engineering stance of Industry 5.0 framework to the modern version of cybernetics.

Definition 1 (*Cybernetics 5.0*) A transdisciplinary framework that proceeds in two directions simultaneously, and aims to:

1. embed the scientific, technological, and engineering practice of Industry 5.0 into the socio-economic-humanistic playground;
2. endow Industry 5.0 with the powerful means of 2^{nd}, 3^{rd}, and higher-order cybernetics to tame complexity.

Beyond the future of the I40/I50 evolution, next section will express how the cybernetics approach (and so Cybernetics 5.0) relates to recent approaches based on system of systems.

Cyber-physical systems of systems and perspectives for HMT

With the complexity and dynamics of the production process, holistic approaches rely on large-scale complex system composed of operationally independent and management-independent constituent systems like SoS (systems of systems) (Jiang et al., 2024). A subset and specialization of SoS are the CPSoS (cyber-physical systems of systems) that consist of multiple interconnected and interdependent CPSs

(Engell et al., 2015). These systems are designed to achieve a common goal or mission while maintaining operational and managerial independence. This is, as we will discuss in a moment, one of the main features of holonic systems and architectures and thus of the HMT (Holonic Management Tree) recalled here from "Background and recall of the Holonic Management Tree technique" section.

The CPSoS concept can be used to integrate all the components and technologies coming from ICT (information and communication technology). This means integrating several technology definitions, including: Cognitive CPS (CCPS) and Cognitive Digital Twins (CDT) (Ali et al., 2024; El Kalach et al., 2024), industrial CPS (ICPS) (Zhang et al., 2022), AAS (asset administration shell) and multi-agent systems (MAS) (Reinpold et al., 2024; Sakurada et al., 2022; Seitz et al., 2021), extended reality (Tang et al., 2023), along with other means for simulation, modelling, and prediction that make use of AI or other techniques. For example, a CPSoS could include CDTs as subsystems to manipulate knowledge, information and data from some CPS parts of the overall system. This would enable real-time monitoring, simulation and optimisation. Furthermore, the CPSoS as a whole could be a cognitive system, capable of learning and adapting its behaviour based on inputs from different cognitive digital twins and other data sources. In this paper, CPSoS will be used as a general concept to connote all integrated ICT technologies, as the focus is on the ability of a CPSoS to decompose the complexity that general systems present due to its variety.

The first issue in approaches that decompose a CPSoS in order to reduce complexity is the effective decision on suitable granularity. CPS system architectures attempted to define a suitable granularity of the components (Ribeiro, 2017) whilst taking into account their integration in a cloud of services (Colombo et al., 2017; Ribeiro & Björkman, 2017). Current trend against (computational) complexity relies on disembodied cloud solutions, but for overall sustainability and performance computation will have to regain body and locality (Ribeiro & Björkman, 2017). The most important design feature is to endow components with enough autonomy in order to enable localized adaptation, resilience, self-healing, self-configuration, self-protection, self-awareness, and evolution through general self-organizing mechanisms at different layers of some flexible but hierarchical structures (Bonci et al., 2019). In this sense, the use of AI is still quite low in the real field, in particular for SMEs (Stentoft et al., 2020). The criteria for autonomy and dynamic assignment of granularity of the operations is still in search for a viable design criteria. Recently, an effort for the standardization of the definition of autonomy with a well-detailed taxonomy has been proposed (Peres et al., 2020).

Agent-based computing paradigms and Multi-agents systems (MAS) schemes have been so far promising for scalability and complexity reduction (Reinpold et al., 2024; Zhang et al., 2019; Seitz et al., 2021). The path of MAS is still not complete, as many barriers can be identified against their factual introduction in industry Karnouskos and Leitao (2016); Leitão et al. (2022). Nonetheless, a standardization work has keenly achieved guidelines for the pragmatics of introduction of industrial agents (IEEE Std , 2021; Leitão et al., 2021), by the IEEE IES Technical Committee on Industrial Agents (TCIA) (Ribeiro et al., 2017). A prominent contribution in this sense has been also provided by the International Electrotechnical Commission (IEC) 61499 standard (Lyu & Brennan, 2020; Zoitl & Strasser, 2017), which keeps the door open to higher computational tiers, like MAS, AI, and distributed autonomy across networks (Seitz et al., 2021).

CPSoS have to rely on flexible functional entities that may be decomposed into sub-components, whilst being coordinated by some higher abstraction entity (Ribeiro, 2017), without a well-defined a-priori granularity (Bonci et al., 2018b). The granularity choice is often difficult in the systems of systems that are inherently multiscaled and open-ended at the top and the bottom. In Fig. 2, it is shown pictorially how a holarchy (a hierarchy of holons, or holons of holons) inherently can be used as a structure that can be left open at the top and open at the bottom. This property derives from the capability of the holon to straddle relationships between parts (at a lower level) and the whole (at an upper level).

For example, Fig. 2 refers to the tree structure defined for the HMT in (Bonci et al., 2019a). In the HMT, the leafs and the root of the tree are to be considered pseudo-holons. A pseudo-holon is a holon only potentially, in the sense that the relationship to an upper whole or lower parts can be left unspecified until they are needed for an expansion or redefinition of the holarchy (upwards or downwards). In this way, the granularity of the holonic CPSoS decomposition remains recursive as desired.

Recursive structures like these are a well-known method for the reduction of complexity (Cardin et al., 2018; Derigent et al., 2021; Hoang et al., 2011; Le Mortellec et al., 2013; Yolles, 2021). For example, the multifaceted model of the RAMI 4.0 reference architecture (VDI/VDE , 2015) can be covered in its multiple dimensions with a holarchy that pursues overall goals and specific sub-goals. In general, using holarchies any industrial eco-system can be mapped into a generic form of a value creating organization (Mella & Gazzola, 2015).

In such a context, all the agents, human or artificial, that enact a holon entity are organized as purposeful producers of value (emerging) at any level of the SoS. Value can be financial, social, or a well-accomplished set of tasks in any of the modelled dimensions. Individuals and the other entities acting in such systems are holistically linked and so responsible

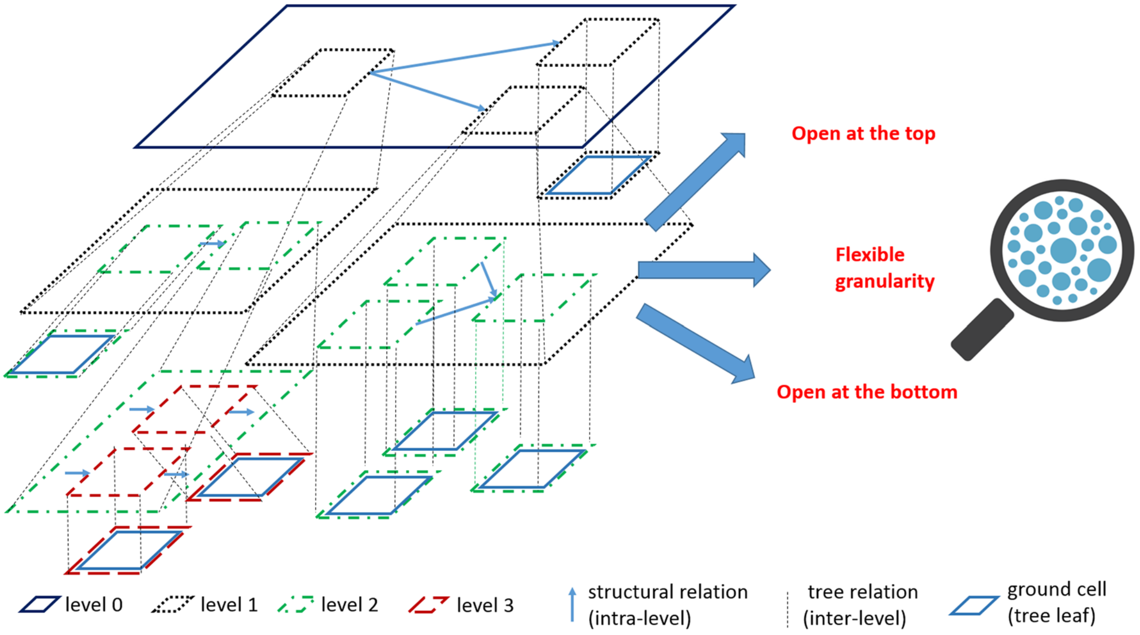

Fig. 2 Holonic Management Tree structure seen as open holarchy

for their own actions and behaviour with respect to the other individuals and the whole vital entity.

In Fig. 3, the CPSoS is the controller of a complex reality in a cybernetic loop. According to the famous theorem of Ross Ashby about good regulators (Conant & Ross Ashby, 1970), the CPSoS must have the same variety of the SoS in order to control or manage it. Supervenience and emergence phenomena at different levels of the SoS can, in principle, be mapped with suitable realizations of a CPSoS, which in turn can be conveniently implemented with holonic multi-agent systems.

In the process of modelling complex reality, the holarchical approach allows parts of it to be left unspecified in the structure, so that extensions can be left open and new structural branches can be created on demand and on purpose. The major concept driving this stance is the D4U (design for unexpected) from Valckenaers & Van Brussel (2015). A lesson from the D4U is to avoid the risk of over-commitment that hinders in general adaptability and resilience. It is well-known, for example in machine learning, that over-fitting blocks generalization in predictive systems. Over-commitment stifles good controllers; CPSoS designers must not add restrictions, which are absent in the corresponding reality (Valckenaers & Van Brussel, 2015).

Definitely, the main concept in D4U design is the supporting of *lazy* development: to specify the minimum viable attributes of an entity and leave plenty of room for subsequent refinements and evolutions. Laziness supports second-order or meta operations in the modelling and opens the door to methods that abide by the autonomic computing vision (Kephart & Chess, 2003). For example, a factory model should include a sub-model corresponding to the world outside the factory (Valckenaers & Van Brussel, 2015). This model, initially a mere placeholder, is then refined when details on exogenous events affect the productions, for example in terms of fluctuations in raw materials or change on market requirements. Holonic approaches can absorb these fluctuations and be fit to implement the new self-x capabilities for CPS coming from the autonomic computing background (Bonci et al., 2019; Lalanda et al., 2013).

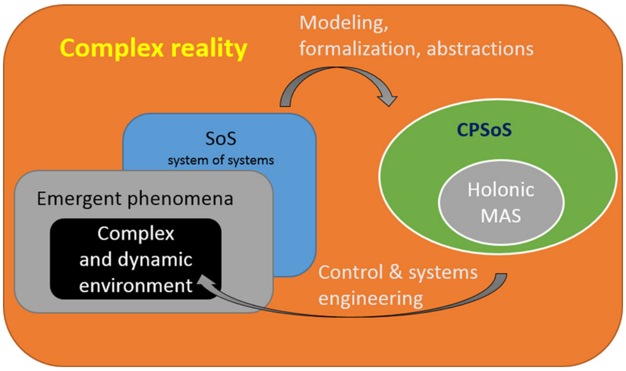

Fig. 3 The circular process of covering realities with SoS in order to establish holarchies and CPSoS for the harnessing of complexity

Background and recall of the Holonic Management Tree technique

The holonic management tree (HMT) (Bonci et al., 2019a, b) is a technique for decomposing a complex problem into recursively and hierarchically related sub-problems. The structure of a HMT is a tree (Fig. 2), at any node of which the sub-tree of descendants constitute a new whole. A node in turn belongs to an ancestor and causally influences it whilst maintaining a holistic control of the sub-tree of its descendants.

Typically, for example in manufacturing, complex relationships between different elements and actors of a work cell originate from the integration of multiple layers of hardware and software (Sharp & Weiss, 2018). In these situations, holonic control architectures (HCA) have been the most promising control schemes during the last 20 years (Cardin et al., 2018, 2022; Derigent et al., 2021). A HCA is composed of holarchies that are purposeful emergent organizations of holons featuring self-similarity. When such a hierarchical structural decomposition is possible, HMT applies seamlessly; systems are decomposed functionally and structurally with flexible granularity into entities that potentially extend their action scope from the infinitely small to the infinitely large. That kind of structuring considers the system's whole as an organization of behaviours emerging from semi-autonomous parts, which performance can be measured and possibly improved. The patterns of behaviours may be complex and dependent on requests of the structural adjustments triggered by performance indicators (Yolles & Fink, 2011).

The HMT is in essence a new way of defining a recursive set of KPIs (key performance indicators) which can consider both vertical and horizontal recursion (Smith & Shaw, 2019; Yolles, 2021). Recursiveness, assumed as the main structuring requirement, connects HMT to the management cybernetics discipline and to the Beer's viable system model (VSM) approach, which encompass seamlessly services and processes (Vahidi et al., 2019; Yolles & Fink, 2011; Yolles, 2021). In Bonci et al. (2018b), a new cyber-physical viable system (CPVS) model is defined, which unifies the holistic and teleological production goal of cybernetics with the KPIs connected to performance measurements. The key for the HMT to address the definition of multi-dimensional KPIs required by the cybernetics approach can be found more developed in Bonci et al. (2019b).

The range of applicability of the HMT principles are seen, for example, in Stadnicka et al. (2017) and Indri et al. (2018). In Stadnicka et al. (2017), KPIs are used for the control and decisions where the human component is mixed with a CPS automation basing on a value-creating Ishikawa model that connects causes and effects of inefficiencies. In Indri et al. (2018), a first development of the technique can be found in robotics context.

A first step in the path towards complexity reduction and management corresponds to first-order cybernetics, where a model of objective reality is used for the management and control of a (temporarily) stable problem or process (Bonci et al., 2019a). Even before the technique was given the name HMT, the essence of it had been growing through several challenges in different application domains as robotics (Bonci et al., 2017b; Indri et al., 2018; Pirani et al., 2016), in building management (Bonci et al., 2019; Carbonari et al., 2018; Carbonari et al., 2020; Naticchia et al., 2019; Pirani et al., 2018), in manufacturing processes (Bonci et al., 2017a, 2018c, 2019b; Stadnicka et al., 2017), and in services and lean management (Stadnicka et al., 2017).

The main characteristics and idea of the HMT methodology and technique stemmed from the observation that fractal structures occur in many production processes and their machining. Hence, by attributing a recursive model to the self-similar structures of the controllers, at the many levels of the SoS, a simple and general tool for their continuous improvement was obtained by means of the HMT definition. This tool was proven effective for a bare-metal implementation on very tiny CPS devices (Bonci et al., 2018c), in order to scale down to the *Edge* of distributed controller networks.

In proper cases, due to its extreme simplicity, the HMT can be even suitable for hand-made calculation from humans. This feature is compliant with an immediate dynamical collaboration between humans and machines at the many levels of the control hierarchies and architectures, as envisioned by the recent multifaceted trends about human-centric visions in CPS for I40/I50, see for example (Hasbach & Witte, 2021; Jones et al., 2018; Ma et al., 2017; Rauch et al., 2020; Romero et al., 2016, 2020; Stadnicka et al., 2020; Sony & Naik, 2020; Yao et al., 2024) and references therein. According to E. A. Lee, "We are seeing the emergence of symbiotic coevolution, where the complementarity between humans and machines dominates over their competition." (Lee, 2017, 2020).

Current limits of the HMT methodology are to be found mostly in the phase of the construction of models and structures of the HMT and their continuous refinement. This problem pertains to higher order cybernetics where meta levels of design and modelling usually occur. This problem, applied to the I40/I50 context here has been defined as the *Cybernetics 5.0*. The new developments on HMT here proposed will candidate it as a first set of viable solutions for the Cybernetics 5.0. The holon is the *glue* that controls the emergence from parts to the whole, linking the behavior and purpose of two levels in a tree.

With the introduction of holons, a hierarchy becomes a holarchy that features holons as constituent nodes (Calabrese et al., 2011). Holarchies constitute structures that can be overlaid on a cyber-physical system of systems that acts as a controller of a complex and corresponding system of systems (Bonci et al., 2018b).

A peculiar position in HMT is that a holarchy is interpreted as a decomposition of goals. This means that each holon maps a sub-goal corresponding to a sub-process that expresses a local purpose in the holarchy. The purpose is pursued through the organizing force of the holon that coordinates its parts in order to achieve its own goal. This is a teleological interpretation of the holon, which creates the link with the cybernetics principles and the related teleological interpretation, as treated in "Cybernetics 5.0: Teleology of Production Management and Control" section. It is precisely by defining a holon in association with a goal that we create a *Teleological* interpretation of holons. In order to give here a prompt and summary handle of the definition of *Teleological* interpretation we can provide the following definition.

Definition 2 (**Teleological holon**) A holon, under Teleological interpretation, is an entity that expresses some mechanism, process, or structure that fulfills simultaneously: a) a goal as a participating entity, as a part of a superordinate goal; b) a (self-)goal that is achieved as a whole but caused by a set of subordinate entities and their own associated goals.

In such Teleological holonic systems, a systematic resolution process can map target goals to cause goals, as long as they are provided with a decomposition in system of systems, and recursively. A similar hierachical decomposition was explored by Giunchiglia and Fumagalli (2017). The Teleological interpretation of the holon definition provides means to include also such kind of results about knowledge representation, and at the same creates a natural direct integration into the cybernetics of purposeful actions. This process may be implemented by means of various techniques as treated in (Diaconescu et al., 2016). HMT is one of those techniques.

The holonic paradigm in HMT constitutes the doubly-faced link between one level of the tree and its descendants—known as the *janus effect* (Koestler, 1968). A node of the tree is a holon, that coordinates purposeful relations among its children. The children are linked by causal relations in 4 topological structures, namely *series*, *parallel*, *assembly*, and *expansion* (Bonci et al., 2019a). Figure 2 shows a HMT with 4 levels and a total of 11 tree nodes. At first level (level 0) the root node is a pseudo-holon (not explicitly linked to parent or upper whole) that coordinates an *expansion* structure of 3 nodes at level 1. At level 1, one of the nodes contains a leaf, and so a pseudo-holon which parts are lazily not detailed yet. The other two nodes at level 1 are holons coordinating respectively a *series* and an *assembly* structure. The parts of the latter are found as leaves at level 2. The parts of the former are a leaf at level 2 and a holon at level 2 that coordinates a *parallel* of parts down to the level 3.

Due to the Teleological interpretation, each node of the tree is associated to a goal, and then to a measurement of the degree of achievement of a goal, typically by means of a key performance indicator (KPI). Among the many choices available for KPIs, the HMT methodology uses a comprehensive key performance indicator which is the most used in manufacturing, namely the OEE (overall equipment effectiveness) (Stamatis, 2017). The OEE measures simultaneously the efficiency, the quality, and the availability in the process of reaching a goal.

In the HMT, the OEE can be applied directly only to the pseudo-holons taking the role of the leafs of the tree. The leafs are indeed the only entities that can receive sensing information from the environment controlled by the holonic system. To get a measure of effectiveness at other nodes in the tree as well and at the same time identify bottleneck subsystems, the key to the technique is to associate an OTE (overall throughput effectiveness) with the higer-level nodes. OTE's value depends on the OTE of descendants recursively.

A first version of the formulas that link OTE to OEE was derived from the original studies in manufacturing due to (Muthiah & Huang, 2007). The final and top OTE (the OTE of the root) is recursively determined across all the nodes of the holarchy through a straightforward bottom-up computation, once the leaf of the tree are valuated with an OEE. More details on the formulas and the behavior of the bottlenecks obtained by this computation can be found in Bonci et al. (2017b, 2018a, 2018b, 2018c, 2019), Pirani et al. (2018), and Indri et al. (2018).

A remark must be made on the choice of the OEE as primary indicator for HMT. It is typically a statistical and off-line measurement of performance. In HMT, its meaning and definition has been extended in order to comprehend even on-line and real-time measurements of performance of very different nature that depends on the level at which it is applied (Bonci et al., 2019b). The name OEE has been retained (maybe a bit misleadingly), but its semantics and definition in HMT is context-dependent as we will see in the following. When the OEE is valuated at real time, the HMT itself can be seen as a particular DT with situation awareness (Müller et al., 2024) and, as we will see below, the MHMT will be the systematic procedure to let the DT evolve and adapt.

There are many variants of the OEE (Stamatis, 2017), but a most practical and generic generic expression for the OEE can be given as in Bonci et al. (2019a), Muthiah and Huang (2007), and Stamatis (2017), as follows:

$$OEE = A_{eff} \times P_{eff} \times Q_{eff} \tag{1}$$

where A_{eff}, P_{eff}, and Q_{eff} are the three factors that model availability, performance, and quality, respectively. *Availability* concerns features and repairs, which are set-up time and other losses due to temporary unavailability of the systems that perform a process. *Performance* is about the speed of machinery and focuses on reduced operating speed and minor stoppages. *Quality* addresses defect losses, focusing on scrap and rework, as well as start-up and rework.

In HMT, the meaning of the three performance factors A_{eff}, P_{eff}, and Q_{eff} is extended, and a mapping is made between each of them and the goal of a process. In Diaconescu et al. (2016), a goal is considered any valuable property, state or behavior that is going to be achieved. For HMT the goal is simply a production performance target. A simple and natural semantic mapping can be always made between the definition of the goal parameters and the generic OEE formulation of given from (1). In Diaconescu et al. (2016) and Frey et al. (2015), a goal is associated to a compound of constraints associated to a triplet (V, S, R); for the OEE, which is the basic goal measurement in HMT, the triplet is $(A_{eff}, P_{eff}, Q_{eff})$. With the help of Table 1, details on such a mapping can be made. This mapping expands the semantics of OEE to a more general scope, albeit in a systematic way that may be prone to automation in some of its parts.

The main aim of the HMT is a temporary reduction of complexity, not an optimum search. Once the OEEs and the structural relations are defined (as detailed in "Construction and definition of the OEE KPI: the HMT kernel" and "Construction of the Structural Relation: the HMT structure" sections, respectively), HMT can be used as a predictor, a reasoner, and a decision support system. HMT suggests a set of control actions that should guarantee a monotonic improvement of the performance of the whole system towards its goal.

Many problems remain still open for HMT. The first is a typical and natural evolution during time of the controlled complex system. The second, is the necessarily inaccurate modelling of the OEE that always occur in practice. These first two problems alone create unavoidable difficulties and diminishing returns.There will always exist a point in space and time when the structural relationships and granularity of the HMT holarchy will begin to fail to adequately adhere to the reality under control. Due to the inevitable cost and time constraints inherent in the definition of complexity, any instance of HMT is bound to fail at some point with respect to the monotonicity property of performance improvement.

Nonetheless, this behavior is part of the design of HMT itself and a feature. Actually, HMT is also a "sensor" that provides and alarm about a malfunctioning of the models. When this alarm is raised, a procedure must be undertaken to throw away the old HMT and refine it into a new one, until its effects subside again.

In order to create a solid and systematic procedure for HMT handling and refinement, a suitable framework was also devised, as will be recalled in the next section.

The RISSA framework as a meta model for HMT

The arrival of new sensing data through some acquisition process (manual or automated) determines an update of the values of OEEs and OTEs; bottlenecks are identified in association to the parts of the system with lower OTE or OEE values. At the same time, by singling out a leaf element among the bottleneck set, HMT will suggest a set of maximum available (theoretical) increases of the OEE factors on the selected elements, namely A_{eff}, Q_{eff}, P_{eff}, or k_n in case of *assembly* or *expansion* structures (Bonci et al., 2019a).

To any feasible increase of the value of the OEE will correspond an improvement. For example, setting a new *override* value for a robotic arm as in Indri et al. (2018) to improve the energy and efficiency trade-off in manipulations.

After the acquisition/sensing phase, HMT can be used to anticipate or predict the theoretical improvement achievable at the next iteration. At the next iteration of the sensing (corresponding to a valuation of the OEEs), if the expected improvement is not achieved (or not close to expectations) an alarm is triggered. This signal will simply mean that the consistency of the underlying models has been lost and that the HMT needs to be "repaired" in order to continue to suggest factual improvements on the controlled system or process. When HMT raises its alarms concerning loss of efficacy of its models, a second order cybernetics process comes into play. At this point, two cybernetic loops have to appear.

The first is the short-term loop that corresponds to a first-order cybernetic feedback control, about the sensing and control loop which purpose is to minimize a distance between desired theoretical performance and actual measurements; the controlled process is the *object* of continuous improvement. The use of the emphasis for the term *object* is to highlight the adoption of a classical type of scientific rationality in order to define and handle the first-order cybernetics nature of the phenomenon. After the *object* of reality has been "frozen" inside the HMT, with parameter valuations due to observer and the context, it becomes a classical item for the application of control and systems engineering methods. In such a state, the HMT can be seen as a tool for the management of a control system.

When an alarm event is triggered as a "suffering" state of the HMT, a second-order cybernetics loop is called in. This corresponds to some sort of irritation for the agent that embodies the HMT – as irritation of agents is defined by Füllsack (2014). The cybernetic loop that constitutes a second-order cybernetics phenomenon is activated in order to solve this irritation. A meta level has to be activated now, when the first-order loop signals have lost their consistency and efficacy, and the predictions carried out from the current instance of the HMT do not match the evolution of *objective* reality anymore.

A meta-level must be activated now, when the signals of first-order loop have lost their consistency and effectiveness and the predictions made by the current instance of the HMT no longer correspond to the evolution of *objective* reality—which is better described by cyberneticians as *objectivity-in-parentheses* (Espejo, 2022).

Table 1 Semantic mapping between the meaning of the factors of OEE and the more general framework on goal-based holonic agency of Diaconescu et al. (2016) and Frey et al. (2015)

Goal's constraint as in Diaconescu et al. (2016) and Frey et al. (2015)	Semantic mapping between alternative interpretations of goal parameters		**OEE factor**
	Interpretation of goal constraints as in Diaconescu et al. (2016) and Frey et al. (2015)	Interpretation as OEE in production context	
V	*What*. A viability constraint defining the system's desired state space or behavior	A measure of the quality of outcomes. For example, performance of an autonomous vehicle that is asked to follow closely some path or trajectory	$\mathbf{Q_{eff}}$
S	*Where, Who*. A spatial and physical scope constraint defining where, or over which managed resources, the actions that pursue *V* are conducted	Availability of resources. For example, the available free space for maneuvers or degrees of freedom along with energy resources available for a robotic vehicle	$\mathbf{A_{eff}}$
T	*When*. A time constraint defining when *V* is to be applied and evaluated	Timeliness or speed. For example, adherence to the exact period in which desired behavior had to be performed	$\mathbf{P_{eff}}$

At this point, an observer of the second order has to plan and handle the refinements needed to modify and re-spawn the a new improved HMT that overcomes the limits found in its previous version. This process calls in non-classical type of scientific rationality. In this rationality, the observer constructively considers subject and object as a whole, through a relation of reflexive-active control (Lepskiy, 2018; Raikov, 2019).

Among the many possibilities for the handling of this second order loop, the *RISSA* framework, firstly found proposed by Bonci et al. (2018a), is reformulated and improved here in a more complete form, to pursue a viable attempt in order to find a convenient systematic expression for processes that require a cybernetics of the second (or third order). In Fig. 4, two main cybernetic loops are highlighted. The loop of the first order involves the *STATS*, the *IMPROVE*, and the *APPLY* phases of the HMT. This loop corresponds to the basic application of the HMT, as it was treated with differing details and domains in Bonci et al. (2017b, 2018a, 2018b, 2018c, 2019), Pirani et al. (2018), and Indri et al. (2018).

The second-order cybernetics loop involves the *STATS*, the *REFINE*, the *SPAWN*, and the *APPLY* phases. In the following list the semantics of these phases are recalled.

- *REFINE*. This phase is to refine the model that underlies an instance of the HMT. The HMT models the world of interest of the managed process, but when its efficacy is lost (or at the first HMT instance), the REFINE phase is needed to determine both the KPIs and the structural relations that make up the HMT. This step needs knowledge and reasoning, along with a consistent causal worldview. The observer and the reasoner can be human or artificial. In the case of artificial, the technologies involved should feature abductive and other non-monotonic logic capabilities, artificial general intelligence (AGI), and causal reasoning.
- *IMPROVE*. In this phase, the HMT mechanism provides a possible set of choices, by indicating a maximum amount of improvement available for selected OEEs (Bonci et al., 2017b, 2018a, b; Bonci et al., 2019; Pirani et al., 2018; Indri et al., 2018). In this phase one of the choices is assessed and singled out. The choice will correspond to an action that could be selected among many with respect to feasibility, overall costs, policy, availability, and other pragmatic criteria. The amount of improvement chosen is based on a short-term prediction. The actual effect will be verified at the next *STATS* phase. If the difference between prediction and actual effects are not acceptable then another *REFINE* phase is triggered.
- *STATS*. Is the acquisition/sensing and measurement phase, in order to measure the current performance of the system. The OEEs and OTEs (Muthiah & Huang, 2007) are valuated with respect to their definition. Contextually some bottlenecks are detected. They indicate which nodes of the HMT are prone to improvements. Bottlenecks are here to be interpreted as opportunities for improvement. This will produce the set of elements of HMT that feed the *IMPROVE* phase (Bonci et al., 2017b, 2018a, b; Bonci et al., 2019; Pirani et al., 2018; Indri et al., 2018).
- *SPAWN*. This phase contains the process conducted to spawn a new or partially modified HMT instance. This is the phase more prone to a complete automation. It is indeed systematic due to the well-defined expressions of the HMT structures and formulas that can be adopted in this phase.

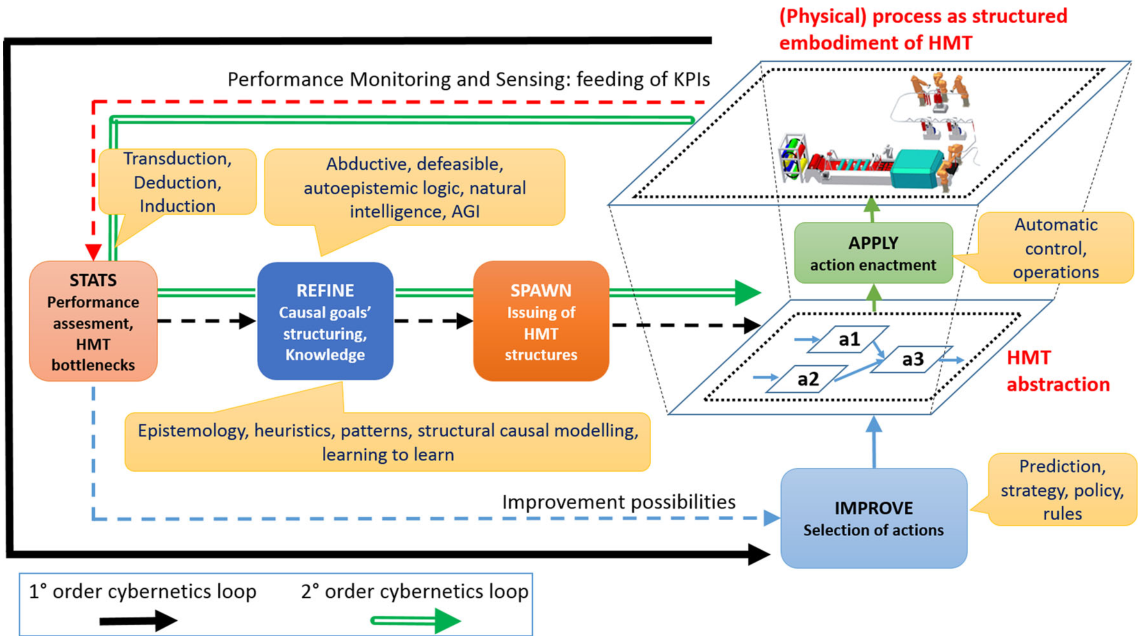

Fig. 4 The RISSA as framework for HMT meta processing

- *APPLY*. Is the phase that contains the provisions for the *enaction* of improvements. This accounts for the non ideality of the application of an improvement action as predicted by the *IMPROVE* phase. Typically, the action can be a complex process by itself, conducted manually by an operator and her skills, or automated when suitable provisions are possible and present. For automated agents a parallel can be made with hierarchically organized deliberation according to Ghallab et al. (2014), which can be used to decompose and reduce the complexity of an action.

Note that the cycle containing the *REFINE* stage is the central mechanism for the transition to higher-order cybernetics, as well as the beginning of the metaprocesses for HMT. In this phase dwell most of the scientific and technological challenges for future applications of the HMT methodology. Other phases like *STATS*, *SPAWN*, *APPLY*, and *IMPROVE*, are prone to more straightforward approaches based on already available technologies and methodologies for intelligent automation and AI. Nevertheless, as remarked by Bonci et al. (2019a), the HMT in principle can simply rely also on a pen-and-paper computation procedure.

The issues on scalability and sustainability of the computing required to perform the REFINE phase remain a sensitive design constraint. However, the flexibility and variable granularity of the HMT elements are a built-in strength against computational complexity, at least up to a certain but still useful extent.

In the next section, the focus will be posed on the *REFINE* phase. It is the most critical phase in terms of AI an automation. It is in this phase that the whole HMT technique gains a factual general utility by creating structures to confront with complex scenarios.

The MHMT methodology against complexity

The HMT is a tree of holons which constituent elements are subject to some structural constraints. The first constraint is in the relationships between parts and wholes. These relationships are not free but chosen among 4 possible structural relations, namely *series*, *parallel*, *assembly*, and *expansion* (cfr. Fig. 2). This structural restriction is made in order to create a finite set of possibilities, still maintaining enough generality to cover effectively a broad set of causal relationships. The number and nature of these structures has been inspired by the work of Muthiah and Huang (2007). This constraint also defines how the performance of the wholes, accounted with OTE, depends recursively on the OEE of the constituents children in the structures.

Beyond these structural constraints, the other constraint is the definition of the KPIs and so the choice of the very simplified and generic (semantically extended) expression of the OEE as recalled in “Background and recall of the Holonic Management Tree technique” section.

While the tree structure of HMT is determined by design, namely the *tree relation* (Bonci et al., 2019a), the holonic construction of KPIs and the *structural relation* remain two major challenges in order to look for an systematic approach prone to automation of the second-order HMT process.

In the following, the two problems of KPI construction and structural relation will be thoroughly formalized towards the aim of creating a solid ground for the definition of the MHMT (meta HMT) systematic procedure. Such procedure is the key step for the handling of the HMT structures in a systematic framework that can be applied when a complex process is to be harnessed in order to gather control over systems' performance and their teleology.

In this article, we take the opportunity to define for the first time the two main parts into which the HMT can be decomposed, which are given the names *HMT kernel* and *HMT structure* respectively.

The *HMT kernel* concerns the models and the formulas that define the OEE. This is essentially the part that contains the contact between the cyber part with the physical realm — whenever physical makes sense, as HMT could be applied also to complex virtual or abstract systems and DTs in general. The *HMT kernel* is the part more prone to future changes as it can be considered a plug-in. The formula used to model and compute the OEE may take numerous and alternative forms, beyond what have been tested so far.

The *HMT structure* concerns the emergence of the parts into the wholes with a fractal and self-similar recursion of the elements across the holarchy associated to the HMT. In "Construction and definition of the OEE KPI: the HMT kernel" section the current and usual expression of the HMT kernel will be addressed, while the *HMT structure* will be the focus of the "Construction of the Structural Relation: the HMT structure" section.

It has to be noted that the control in the sense of regulation is not achieved directly by HMT. HMT is a meta-level itself on the underlying control systems that make it pursue its production purpose. HMT corresponds to a first-order cybernetics and, as such, is a manager of the controllers and the automation at the 0^{th}-order cybernetics. Such a methodology is affine to the class of reinforcement learning methodologies and dynamical programming. Basing on the results of certain actions, the owner of the HMT can navigate the evolution of complex processes and guarantee a *satisficing* level of performance. But the following of the continuous evolutions in complex situations and the uncertainties in the reality modelling require a continuous change of the world view and of the assumptions and structures that try to follow the reality. This is why the MHMT is an essential step and procedure in order to let the higher-order controller continuously switch across several instances of HMTs.

Typically, The MHMT will need some kind of cognitive processes, being them natural or artificial. The problem of the complete automation of MHMT can be paralleled to the long living but still unsolved problems in *situated cognition* (Clancey, 1997), human-like AGI (artificial general intelligence) (Russell, 2021), and lifelong autonomous learning and self-adaptation of agents (Weyns et al., 2023; Gheibi & Weyns, 2022). In essence, the problem is that of modelling and then automation of the construction processes underlying technical and practical knowledge, for any agent that tries to escape complexity. The inherent dynamical complex cognitive nature of MHMT contains the actual hard part of the problem. MHMT constitutes, in this sense, a reference challenge and benchmark for the future solutions of the *situated cognition* problems that still pervade many aspects of current technologies for artificial intelligence (Ravichandran et al., 2021).

Construction and definition of the OEE KPI: the HMT kernel

The *HMT kernel* is the part that contains the modelling of the world of interest. In particular, when the world of interest is the physical world, this part contains the models and the formulas that make up the key performance indicators, which are at the core of the HMT technique. It should be noted immediately that the definition of the HMT kernel is neither unique nor unambiguous. Other formulations may be created, and the HMT kernel must be considered a plug-in in the building of the HMT itself.

In this section we discuss the only experimentally proven and available instance of HMT kernel to date, while reserving for future work the development of alternative possibilities. A first alternative should introduce Bayesian and probabilistic computation.

Typically, any leaf node of the HMT is associated to an OEE KPI, as recalled in "Background and recall of the Holonic Management Tree technique" section, composed by the three factors Q_{eff}, A_{eff}, and P_{eff}, associated respectively to: a viability indicator, defining the fitness of a system's behavior with respect to the goal that a leaf of the HMT is pursuing; a scope (or spatial) indicator, defining where, or over what, managed resources the behavior is to be evaluated; and a time-dependent indicator defining the timeliness of a behavior. This association is an attribution of semantics that requires the addition of an upper level of interpretation and modelling (see for example Table 1).

In order to establish a systematic framework for the interpretation of OEE factors, the following positions will be taken.

X_{eff} is posed as a generic representative for any of the three factors of the OEE. A function that valuates X_{eff} is established as $X_{eff}(x) : [x_{min}, x_{max}] \rightarrow [\varepsilon, 1 - \varepsilon]$, with $\varepsilon > 0$, arbitrarily small, and $[x_{min}, x_{max}] \subseteq \mathbb{R}$. $X_{eff}(x)$ is the function that determines the value of the OEE and so of the OTE in the *STATS* phase, when $X_{eff}(x)$ is valuated for each of the three factors Q_{eff}, A_{eff}, and P_{eff}.

The graph associated to the function $X_{eff}(x)$ is to be chosen among the class of monotonic invertible contraption functions having $[x_{min}, x_{max}]$ as their domain. Two typical choices for such kind of functions are the straight line and the sigmoid (or logistic) function. The first one is the simplest, though its capability to adhere to natural behaviors of physical phenomena is limited, due to its rather ideal characteristic. The expression for the straight line can be given as:

$$X_{eff}(x) = \frac{1-2\varepsilon}{x_{\max} - x_{\min}}(x - x_{\min}) + \varepsilon \tag{2}$$

such that $X_{eff}(x_{\max}) = 1 - \varepsilon$, and $X_{eff}(x_{\min}) = \varepsilon$.

A typical choice, which mimics the most frequent natural behavior of physical phenomena, is the sigmoid or logistic function. This is still a smooth and differentiable function that takes into account saturation effects at the edges of the $[x_{min}, x_{max}]$ interval. Its expression is:

$$X_{eff}(x) = \frac{1}{1 + e^{-c(x - x_c)}} \tag{3}$$

such that

$$\begin{aligned} &\lim_{x \to +\infty} X_{eff}(x) = 1 \quad \lim_{x \to -\infty} X_{eff}(x) = 0 \\ &X_{eff}(x_{\max}) = 1 - \varepsilon \quad X_{eff}(x_{\min}) = \varepsilon \end{aligned} \tag{4}$$

The expression (3) is a particular case of the most general

$$f(x) = \frac{a}{1 + be^{-cx}} + d \tag{5}$$

with the following assignments

$$\begin{aligned} &d = 0 \quad a = 1 \quad b = e^{cx_c} \\ &x_c = \frac{x_{\max} + x_{\min}}{2} \qquad c = \frac{2\ln\left(\frac{1}{\varepsilon} - 1\right)}{x_{\max} - x_{\min}} \end{aligned} \tag{6}$$

Note that in (6), $x = x_c$ is the point where maximum variations occurs, being it the farthest from the diminishing effects of the curve. A graph of the curve is shown in Fig. 5.

A third kind of function could be a Pareto cumulative distribution curve, as it models many natural phenomena as well. Its expression is left for future developments.

In general, a process of learning, identification or classification can help choose the best curve for a specific class of problems. But the specific optimal choice has to deal with optimization issues, which are left behind for the moment. Actually, it can be noted that the HMT, in principle and in general, can proceed up to a certain point with any definite curve choice, and without concerning about optimality at all. The difference between one choice and the other will correspond to a greater or lesser number of HMT iterations or a more or less accurate model of the performance function. This is indeed just one of the degrees of freedom that can be exploited in the HMT methodology.

In general, the main goal of HMT is not optimisation but simplification, to escape complexity. For this reason, in many cases, a fast-and-frugal solution is heuristically the best choice for HMT by design.

In order to fully define and evaluate the modelling capabilities of $X_{eff}(x)$, we must first define a meaning of x. In particular, since the first focus is on the phase *STATS*, this variable will be written as x_S, letting the subscript denote the phase of the HMT.

In order to endow x_S with an operative definition, x_S can be a functional which value defines a performance level or, alternatively, a measurement of the attainment of a goal by the agency that pursues it. Note that such an agency can be a natural or artificial entity, system, or process.

Let M be the set of behaviors which performances are under assessment by means of the X_{eff} factor. A suitable metric d is associated to M in order to define the metric space (M, d), such that $d : M \times M \rightarrow \mathbb{R}$ is a distance between two behaviors b and b_e, with $b, b_e \in M$. b_e is the expected behavior, denoting a theoretical, nominal, and ideal behaviour that the process is expected to conduct basing on the model of the reality given by observation or the knowledge of it. In contrast, b is the actually observed behaviour. With these positions x_S is such that $x_S(d) : \mathbb{R} \rightarrow [x_{min}, x_{max}]$, with $[x_{min}, x_{max}] \subseteq \mathbb{R}$, such that $x_{\min} \equiv \sup_{b \in M} d(b, b_e)$ and $x_{\max} \equiv \inf_{b \in M} d(b, b_e)$.

The *STATS* phase is activated by suitable events corresponding to data acquisition. They happen at discrete times (in the typical digital and discrete context). By supposing we are at the start of the HMT, t_0 will be the timing of the first *STATS* event. At this time $X_{eff,t_0}(x_{S,t_0})$ is valuated, and the corresponding OEE will be:

$$\begin{aligned} OEE_{S,t_0} = {} & Q_{eff,S,t_0}(q_{S,t_0}) \\ & \cdot A_{eff,S,t_0}(a_{S,t_0}) \cdot P_{eff,S,t_0}(p_{S,t_0}) \end{aligned} \tag{7}$$

where q_{S,t_0}, a_{S,t_0}, and p_{S,t_0} are the performance measurement functionals that correspond to instances of x_{S,t_0}, defined respectively for the three factors Q_{eff}, A_{eff}, and P_{eff}.

In the following, when the context of the notations will be unambiguous, some elements of it may be simplified, as a form of shorthand, for example the reference to the time of definition of a variable or operator, like t_0 or other indexes.

Basing on the values of the expression (7), and then using HMT's recursive formulas to detect improvement opportunities (detected as bottlenecks), the *IMPROVE* phase mechanism of HMT will subsequently produce a possibly non-empty set of theoretical actionable improvement gains (Bonci et al., 2018b, 2017b, 2018a; Bonci et al., 2019, a; Pirani et al., 2018; Indri et al., 2018; Bonci et al., 2018c).

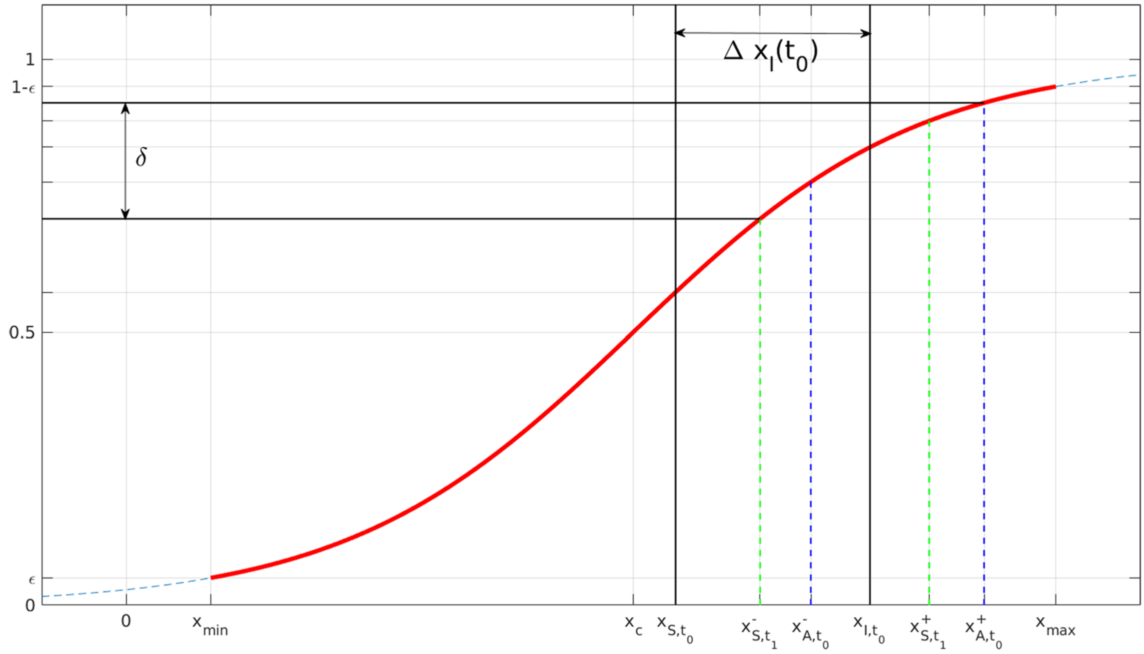

Fig. 5 A graph of a sigmoidal expression of $X_{eff}(x)$ with relevant annotations

In particular, in Bonci et al. (2019a), a practical reference table can be found where the maximum increment available for next OEE or Q_{eff} is given, for each of the resulting situation from the *STATS* phase. This maximum increment value should not be exceeded in order to guarantee monotonic improvement of the OTEs, which are the wholes – the increments of OTE are due to increments in OEEs. The monotonicity property is also lost if the underlying modelling of HMT started to lose efficacy due to unmodelled evolution of the reality during the time sampling period of the *STATS* phase. The monotonicity property is fundamental as it implies that the actions one will chose to apply to the controlled system will not do harm but improve its performance.

One first example of an *IMPROVE* phase is given here, so that the reader can better follow the discussion that follows. Differently from other literature, the aim here is to create a formal treatment of the *RISSA*, not an exhaustive detail on the HMT computation found elsewhere, but a formalisation of it's new MHMT part. A complete and materialized example of MHMT will be provided further in "An explicative example" section.

A *series* structure case of degree 2, corresponding to a tree with the root node and two leafs, is supposed. For such a simple tree the OTE takes the value of (confront with *series* part in Table 3 in the Appendix):

$$OTE = \min\left\{OEE_1\, Q_{eff,2},\, OEE_2\right\}, \tag{8}$$

where OEE_1 is the valuation of the first leaf of the *series*, and $Q_{eff,2}$ and OEE_2 are respectively the Q_{eff} factor, and the OEE for the second leaf of the tree. From this expression it is easy to derive the following context-dependent situation (and conditions, for which complete expression reader may want to refer to Table 3 in Appendix where possible alternative outcomes for an *IMPROVE* phase are provided.

1. First condition (tagged as *S1* in Table 3): $OEE_1\, Q_{eff,2} < OEE_2$. In this case two improvements are possible up to the following values:
   (a) $\Delta OEE_1 = \min\left\{\dfrac{OEE_2}{Q_{eff,2}}, 1\right\} - OEE_1;$
   (b) $\Delta Q_{eff,2} = \min\left\{\dfrac{OEE_2}{OEE_1}, 1\right\} - Q_{eff,2}.$

   In the case (a), the expected OTE increment of the whole *series* will be equal to $\Delta OEE_1\, Q_{eff,2}$; in the case (b), the maximum overall increment will be expected as $OEE_1\, \Delta Q_{eff,2}$.
2. Second condition (*S2*): $OEE_1\, Q_{eff,2} = OEE_2$. This case features 3 possible subsequent moves:
   (a) $\Delta OEE_1 = 1 - OEE_1;$
   (b) $\Delta OEE_2 = 1 - OEE_2;$
   (c) $\Delta Q_{eff,2} = 1 - Q_{eff,2}.$

   Typically, for all these moves the increment will be equal to 0. This does not mean that these kind of moves are useless. Simply, they can be used tactically as intermediate moves in order to drift from a dead point in the multidimensional decision space into a freer one, and so to obtain other available opportunities. The nature of these movements can be found explained to some extent by Bonci et al. (2017b). We remark here also that this case is subject to numerical implementation considerations. The equality (or its approximation) of the triggering condition might not be consistent in most of the implementations, or be treated as a nondeterministic singularity due to a continuous numerical domain in the models (Lee, 2021, 2016).

3. Third condition (*S3*): $OEE_1\, Q_{eff,2} > OEE_2$. In this case only one possibility is available: $\Delta OEE_2 = OEE_1\, Q_{eff,2} - OEE_2$, and the corresponding maximum overall increment will be ΔO_2.

The increments of OEE and Q_{eff} achievable with the former computations are ideal, theoretical, and a maximum, which can be valid only as far as the causal model of reality is perfect. This is rarely the case in real situations. Moreover, the kind of formulas used above do not provide any (physical) meaning about the nature of these increments, and then no hints on what are the actual actions that are to be performed in order to achieve the expected increments. Typically, at this point a prediction is needed to causally link an improvement action to the OEE increment that will be caused by that action. Prediction and causality are in general hard problems, but the construction of the HMT never makes the mistake of confusing the map with the territory (Clancey, 1997; Lee, 2017). In HMT we are aware that the model is a deliberate act of temporary construction and not the ultimate device for controlling a complex reality.

The outcomes of the *IMPROVE* phase are ideal predictions that have to be verified with a subsequent *STATS* phase. Thus, the reader is asked to pay attention at this very important difference in the subscripts: S refers to the measurements; I, refers to predictions. We define:

$$OEE_{I,t_0} = Q_{eff,S,t_0}(q_{I,t_0}) \cdot A_{eff,S,t_0}(a_{I,t_0}) \cdot P_{eff,S,t_0}(p_{I,t_0}). \tag{9}$$

having the S subscript changed into I as a way to making reference to the *IMPROVE* phase for the interested symbols. Where the S subscript is retained, the the function X_{eff} is determined during the *STATS* phase. With former notations, the computation example of (8) may now take the expression:

$$OTE_{I,t_0} = \min\left\{OEE_{1,I,t_0}\, Q_{eff,2,S,t_0},\ OEE_{2,S,t_0}\right\}, \tag{10}$$

supposing that an ideal increment $\Delta OEE_{1,t_0}$ has been singled out, such that $OEE_{1,I,t_0} = OEE_{1,S,t_0} + \Delta OEE_{1,t_0}$.

At this point, a profound problem arises. It is the creation of the meaning of the desired increment $\Delta OEE_{1,t_0}$. An introductory and alternative discussion of this problem can also be found in Pirani et al. (2021), but without the solid formal ground here used.

The question at hand is: what does it mean, in practice and in terms of real improvement actions, to increment the OEE_{1,S,t_0} up to a maximum allowable $\Delta OEE_{1,t_0}$?

In order to answer this question, the first step is to look again into the expression (9), and then to express this increment in form of its possibly separable constituents:

$$OEE_I = Q_{eff,S}(q_I) \cdot A_{eff,S}(a_I) \cdot P_{eff,S}(p_I) \tag{11}$$

with $q_I \overset{\text{def}}{=} q_S + \Delta q_I$, $a_I \overset{\text{def}}{=} a_S + \Delta a_I$, $p_I \overset{\text{def}}{=} p_S + \Delta p_I$, and in general $x_I \overset{\text{def}}{=} x_S + \Delta x_I$.

The meaning of the increment of the OEE will depend on the (possibly) separable effects of the increment from x_S to x_I that defines $\Delta x_I = x_I - x_S$. In Fig. 5, the $\Delta x_{I,t_0}$ interval can be visualized. This interval is the difference between the value of x from the *IMPROVE* phase at t_0 and the value of x from the *STATS* phase at time t_0. Remind that x_I is a variable that can be interpreted, for each of its instances, with the quantities that are linked to the interpretations assumed in Table 1. Note that in general the three factors are neither required to be separable nor the functional relation between them is necessarily expressible in closed form. Such a situation can be found discussed, for example, by Indri et al. (2018) where the improvement action of the OEE for a robotic arm depended, in a rather complex but determined expression, from an single underactuated control variable.

Therefore, for the sake of simplicity and clarity, in the following we will assume that the separability property is valid, and then we focus on the meaning of the expression of each of the variables x_I separately, again using the subscript I to refer to the improvement phase.

The prediction of the improvement Δx_I that will be carried out by performing an action will need the definition of a causal model. The IMPROVE phase generates a set of such kind of values, but the physical meaning and causal modelling related to these improvement quantities have to be established to determine the nature of the action and to predict its effects. This model can be expressed with an invertible law in closed form in the simplest case, but more in general can be a variational effect assessed through a simulation or with the use of a DT. In general it is an inverse problem of finding an action ξ that provides the expected $\Delta x_I(\xi) \leq \overline{\Delta x_I} \subset [x_{min}, x_{max}]$, being $\overline{\Delta x_I}$ the maximum allowable increment that guarantees overall monotonicity of the performance improvement. This increment is computed with the formulas in Appendix, with Table 3, where the third column contains the set of maximum improvement available for each condition and choice of the parameters. The functional that maps ξ into Δx_I can come in two major flavors:

1. The action ξ modifies the current behavior $b \in (M, d)$ such that $d(b(\xi), b_e) < d(b(0), b_e)$, where $\xi = 0$ denotes "no improvement action performed". In this case the $x_I \equiv x_S$, the x functional remains unchanged between phase S and I and $\Delta x_I(\xi) = x_S(\xi) - x_S(0)$.
2. The action ξ transforms the metric space (M, d) into (M, d') through $d' = d(\xi)$, meaning that the action is a modification (improvement) of observability (e.g., perception or sensing capability of the observer) that yields a positive value for $\Delta x_I(\xi) = x_S(d') - x_S(d)$. In other words, this is a change of the metric model that allows the observer to better fit and deepen its understanding of the observed reality, which improves the likelihood of a better control. This change will affects the x functional definition for the subsequent S phase.

It is left to remark that the construction of ξ has to convey the meaning, the feasibility and the costs of the action that is going to be applied to the controlled system. Hence, ξ has to convey the decision making criteria applied.

For example, it contains the overall sustainability of the choices made by a manager. A choice between multiple available and possible actions for the I phase, are typically subject to a selection criteria (which may possibly be automated) that depends on an existing (formal) policy. The singling out of the improvement action ξ may be decided in automatic or manual way in general. The recording of the evolutions of the system in its environment then provide, in process mining mode, parameters that can be in turn used to find a better policy for the agent in similar situations, having the record of the decisions made and the actual effects obtained.

Once the $\Delta OEE_{n,I,t_0}$ is achieved for the leaf n, the new OEE_{n,I,t_0} is input into the corresponding HMT leaf in order to predict the overall expected effects across the whole three evolution at time t_1, and to confront it with the outcome of the next *STATS* phase. The prediction of *STATS-IMPROVE* process may also be repeated over a more extended temporal horizon, depending on the use that is made of the HMT. For example, the HMT can be used as a predictor for control techniques that rely on receding horizons like the MPC (model predictive control) (Kouvaritakis & Cannon, 2016) or other planning methodologies (Wongpiromsarn et al., 2012). Sometimes it is useful to repeat the *STATS-IMPROVE*. This allows a sequence of actions to be planned instead of just one. This, however, comes up against the verification of the effects of each action on the real system and the possible critical effects when nonlinearity is strong. The notation $\Delta OEE_{n,I,t_0}$ and similar should be extended further to include a sub-index that counts the *STATS-IMPROVE* iterations. The index m is added to this purpose to $\Delta OEE_{n,I:m,t_0}$, with $m = 1$ in case it is not explicit.

However, limiting us again at one time step horizon, if the actual value for the n-th leaf at the time t_1 in the new actual *STATS* phase is OEE_{n,S,t_1}, it is likely that it will be different from the expected OEE_{n,I,t_0} due to modelling errors. A performance gap acceptance level δ can be defined such that if $|OEE_{n,I,t_0} - OEE_{n,S,t_1}| > \delta_{OEE}$ then the *REFINE* process has to be triggered.

With reference to Fig. 5, the δ interval depends on two effects. The first is an uncertainty that can appear during the *APPLY* phase. In the application of an action, that is, the enactment of the meaning that the action of increasing x, the actual increase obtained (if readily measurable) could fluctuate in the range $[x^-_{A,t_0}, x^+_{A,t_0}]$, around the ideal x_{I,t_0}. This uncertainty is still detectable and attributable at time t_0 before the subsequent sampling of the *STATS* phase at time t_1. The magnitude of this uncertainty will possibly signal that our model is inaccurate in order to proceed with an accurate enough application of the actions, then a refinement of the model is needed immediately.

The second uncertainty effect, is due to the actual value obtained in the *STATS* phase at time t_1. It is evaluated as acceptable if it falls within the range $[x^-_{S,t_1}, x^+_{S,t_1}]$, otherwise a *REFINE* and *SPAWN* step must be activated before any other *IMPROVE* attempt.

Ultimately, triggering of *REFINE* is due when for any of the definitions of x (q, a, or p) $|X_{eff,S,t_1}(x) - X_{eff,I,t_0}(x)| > \delta_x$, and $\delta_{OEE} = \delta_q + \delta_a + \delta_p$, with $x \in [x^-_{A,t_0}, x^+_{A,t_0}] \cup [x^-_{S,t_1}, x^+_{S,t_1}]$.

The triggering event of *REFINE* phase is designed to push towards better modelling and results with a new instance of the HMT in the interested branch of the tree. This second-order process might involve a refinement of the OEE model or, if not more possible or viable, a complete revision of some parts of the structure containing the n-th OEE leaf, as explained in the next section.

Construction of the structural relation: the HMT structure

In the previous, section the focus has been on the meaning and definition of the OEE key performance indicator, which is associated only to the leafs of the HMT. In some cases or after some time, the models underlying the definition of the leaf node may become poorly adapted to reality. An essential part of the *REFINE* phase, is to refine a leaf into a subtree of its parts, making the leaf a new tree node with its associated OTE. The OTE implies a choice of a structural relation between the sub-parts that in turn become new leafs with their own new expression of the OEE.

This decomposition capability is enabled if the CPSoS is endowed with holonic capabilities and properties. In particular, what is to be decomposed is the goal of the controlled system by mapping it to a holarchy of goals.

Recalling the *Teleological holon* interpretation (see definition 2), any holon entity manages a self-goal possibly caused by a coordination of subordinate entities. This vision is not new and complies with the work on goal question metric paradigm (Caldiera & Rombach, 1994; Van Solingen et al., 2002), goal-oriented holonic systems (Diaconescu et al., 2016), hierarchical composition of self-similar modular blocks (Calabrese et al., 2011), and the Goal Decomposition Tree formalism (Mermet & Simon, 2011), and mostly applied to multiscale and multi-objectives goals (Pahwa et al., 2015; Frey et al., 2015).

OEE and OTE are both associated to a purposeful goal, and to pass from an OEE to an OTE requires a goal decomposition process. A switch from an OEE model to an OTE model is triggered by lack of data, lack of appropriate models, and inappropriate knowledge. The HMT structure can always start with one node being at the same time the root and the only leaf of the tree. The need for further decomposition will naturally arise when the semantics of the OEE of the root becomes untenable.

Let G_1 be the overall target goal, associated to the node 1 of the HMT and then to an OTE that measures its rate of achievement. Initially, if the tree is just the root node, it will be actually measured through $OEE(G_1)$, such that $OTE(G_1) = OEE(G_1)$.

With the use of the holonic property and the structural self-similarity constraints, the *REFINE* phase is triggered to determine what are the sub-processes that can model, explain, and cause the overall target goal G_1. This means dividing the initial process associated to the node 1 into n sub-processess that contribute together to achieve G_1 by pursuing their own respective goals, namely $G_{1,1}, G_{1,2}, \ldots, G_{1,n}$. The performance measurement of $G_{1,1}, \ldots, G_{1,n}$ is transformed into an OTE performance measure of the whole process pursuing G_1.

It has to be remarked very clearly that the structural decomposition adopted for HMT does not have a functional or procedural nature in general. The cause-effect relations between sub-processes and the cause-effect relation between the parts and the whole process are just performance measurements.

The profound transformative effect between parts and whole is the motivation to bring up the concept of holon. The holon, by definition, can handle transformative and emergent effects, the meaning of which is unavoidably fuzzy, blurred, and difficult, if not impossible, to express in formal and symbolic terms.

When an OEE, which models the contact with the (physical) reality, is transformed into OTE, all the details of the physical effects become veiled and opaque. Emergence creates opacity between the parts and the wholes. The whole measured by the OTE can be only accessed in practice through its parts and their new OEEs; the effects on the parts emerge into effects of the whole which manifests its performance towards its goal through the OTE.

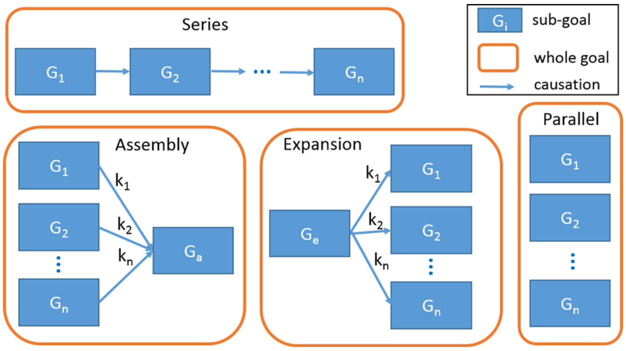

Fig. 6 The 4 structures that realize the causative relations between the performance of sub-processes and their pursued goals

Metaphorically, the OTE can be thought as the measure that rates, for example, the survival behavior of a flock of birds seen as a whole. The movements of the flock become explainable only by observing the movements that are provoked by a predator chasing one bird at time, which individual survival performance can be measured by an OEE. But the causal link between the part (one bird) and the whole (the flock) is difficult to be represented in algebraic expressions and computed in due real time: complexity onsets and emergence is a more effective model. Thus, with OTE we avoid the complexity of the micro modelling but we still need to model and express emergence in a formal way to handle it quantitatively.

The number of ways in which an emergent process can be put in explicit and formal relation with its causative sub-processes is potentially infinite. In order to render treatable and practically manageable the part-whole decomposition, but most of all to keep the process recursive and endowed with self-similarity, HMT adopts (arbitrarily) a set of constraints.

To refine G_1, only 4 topologies (or structures) are available under HMT: *series*, *parallel*, *assembly*, and *expansion*. These structures allow the goal G_1 to be decomposed into a DAG (directed acyclic graph) in which the nodes of the tree are associated with sub-processes. These sub-processes are causative goals connected by the edges of the graph. The edges denote cause-effect relations between the sub-processes, while the whole effect of the structure of sub-processes emerge into the attainment of the goal of the parent node of the HMT tree.

The selection of the fittest structural relation among the 4 allowed is a problem often harder than the refinements of the OEE treated in "Construction and definition of the

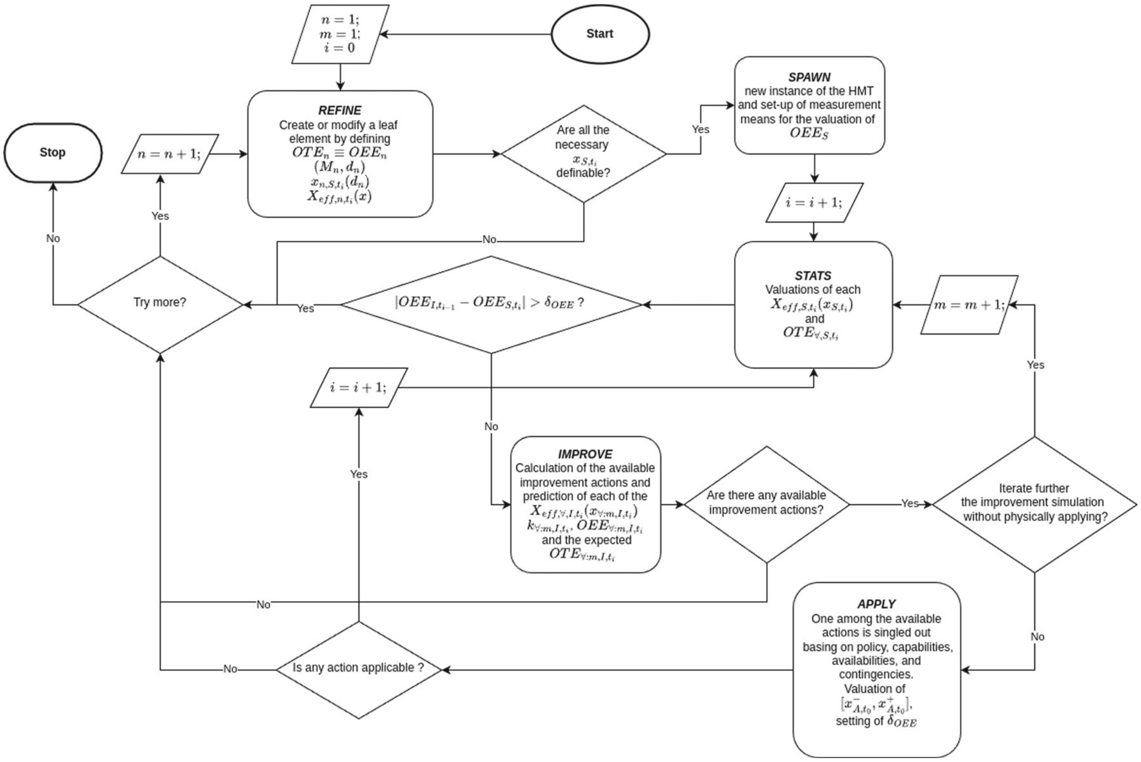

Fig. 7 Overall flow diagram of the MHMT methodology

OEE KPI: the HMT kernel” section. For the automation of this process, some strong tools of artificial intelligence are needed to perform this structuring as quickly and consistently as possible. The decomposition of goals requires some causal modelling in order to determine and define the meaning of the following 4 topologies:

1. *Series*. Every causative goal $G_{1,i}$ is in a causal cascade, where $i = 1, \dots, n$. Any improvement of an antecedent process following the goal $G_{1,i}$ affects causally the performance of the successor process pursuing the goal $G_{1,i+1}$.
2. *Parallel*. The performance of the sub-processes pursuing their $G_{1,1}, \dots, G_{1,n}$ goals concur simultaneously and independently to the performance of the process pursuing G_1.
3. *Assembly*. $G_{1,a}$ is the *head* goal of the structure. The performance of the head process of the assembly is affected by the performance of the sub-processes heading individually for $G_{1,1}, \dots, G_{1,n}$ with weighted contributions $k_1, \dots, k_n$.
4. *Expansion*. The performance of the process pursuing the *head* goal $G_{1,e}$ affects, with the weighted contributions $k_1, \dots, k_n$, the performance of the processes individually heading for $G_{1,1}, \dots, G_{1,n}$.

In Fig. 6 the pictorial rendering of the structural causative relations are shown for the 4 structures.

The search for the appropriate causal DAG structure, among the 4 allowed, is a task that can in principle be aided by intelligence. Among the more promising frameworks in this direction are the SCM (Structural Causal Model) (Cinelli et al., 2019) and the methodologies that adopt Causal Path Analysis (Mohan & Pearl, 2021). These methodologies and tools constitute an advancement of the of the well-known SEM (Structural Equation Modelling) (Pearl, 2012) or Bayesian Network methods (Williams, 2021). The focus for any suitable tool will be the capability to detect causal paths and patterns. In the usual SEM, the G_1 becomes a latent variable, and $G_{1,1}, \dots, G_{1,n}$ the actual observables. Note also that, in the context of SEM the $k_1, \dots, k_n$ take the role of normalized path coefficients. In a very similar acceptation, in HMT the k coefficient is not experimentally observed or determined but is rather an active coefficient acting as a “brake” or limiter of the causal effects, where it has a consistent meaning. In this case, it becomes a manipulation rather than observation coefficient. However, when it is not the case, k remains immutable and takes the role of a normalized SEM path coefficient.

With this causal and topological structuring, the HMT is able to capture in a systematic way the major effects in the complexities of the controlled reality. The limited number of structures and the self-similarity, retained at all the levels of HMT, makes the structuring process viable both for humans and artificial agents. HMT and RISSA, conveyed by

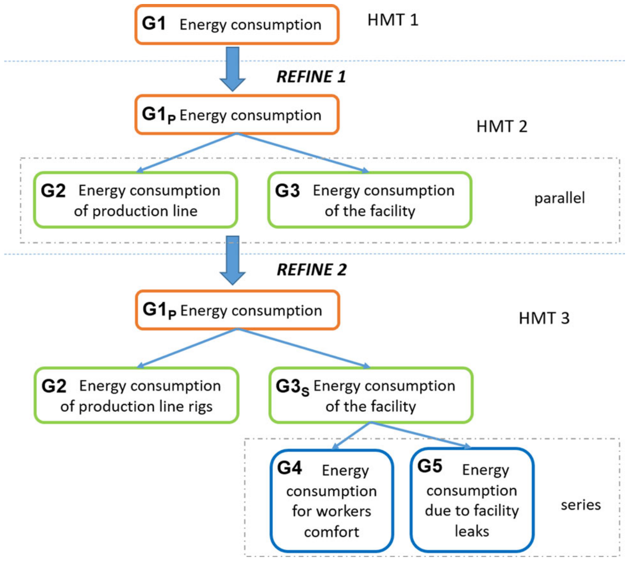

Fig. 8 Evolution of the HMT in the example

the MHMT, constitute a systematic process to incorporate fast-and-frugal decision making in complex contexts (Hafenbrädl et al., 2016).

In Fig. 7, it is shown the flow of the MHMT methodology that summarizes the contents of "The MHMT methodology against complexity" section.

An explicative example

In this section we try to materialize the concepts introduced in "Construction and definition of the OEE KPI: the HMT kernel" and "Construction of the Structural Relation: the HMT structure" sections. The example used here is very limited and extremely simplified, but it must contain the minimum articulation to explore the more relevant parts of the MHMT methodology.

Our example concerns with a generic manufacturing plant of which a manager has to improve the overall energy consumption. The MHMT flowchart starts, as in Fig. 7, posing $n = 1, m = 1$, and $i = 0$. With a first *REFINE*, the root of an HMT is created. The whole tree named HMT 1, and the associated goal $G1$, as of Fig. 8. For $G1$, $OTE_1 \equiv OEE_1$ and $G1$ means "Make manufacturing plant energy consumption lower". For this goal a metric space (M_1, d_1) needs be defined. Manager defines d_1 as the distance that the kWh of consumption in one day is from a desired target value of consumption. At this step, the manager can make a couple of choices to quantify d_1. A first choice is to state a desired ideal value, and measure the current distance to that by checking the energy meter, and then compute the corresponding OEE, having decided *a priori* a suitable range of values. A second choice is to start with a middle point, whatever the meter will say and deferring the choice of the value range that will depend on this position: "in any case we would like to improve starting from the current value of the meter". Following this second choice, manager chooses that the value read on the meter will correspond to $OTE_1 = OEE_1 = 0.5$, $P_{eff,1} = A_{eff,1} = 1$, and $Q_{eff,1} = 0.5$, using the expression (1). The choice of $OEE_1 = 0.5$ means that we pose ourselves right in the center, to be ready to assess differential increments, towards better or worse conditions of the system in reaction to the next actions. It is now important to provide physicality to the model by providing quantities to d_1. Before doing this, some more expressions could be handy to compute the inverse of (2) and (3) as follows:

$$x = (X_{eff} - \varepsilon)\frac{x_{max} - x_{min}}{1 - 2\varepsilon} + x_{min} \tag{12}$$

and

$$x = -\frac{1}{c} ln\left(\frac{1}{X_{eff}} - 1\right) + x_c \tag{13}$$

with

$$x_c = \frac{x_{\max} + x_{\min}}{2} \qquad c = \frac{2\ln\left(\frac{1}{\varepsilon} - 1\right)}{x_{\max} - x_{\min}} \tag{14}$$

and with (12) inverse of (2) and (13) inverse of (3). Another step is needed to choose $x(d)$ and its inverse. Among the many possibilities a simple one works well enough if we choose:

$$x(d) = \frac{x_{max} - x_{min}}{d_{max} - d_{min}}(d_{max} - d) + x_{min} \tag{15}$$

and its inverse

$$d(x) = d_{max} - \frac{x - x_{min}}{x_{max} - x_{min}}(d_{max} - d_{min}) \tag{16}$$

For the sake of simplicity in this example, in defining x and d we will always pose $x_{max} = d_{max}$ and $x_{min} = d_{min} = 0$ to obtain an extremely simplified form of the (15) and (16) as:

$$x(d) = d_{max} - d \tag{17}$$

and

$$d(x) = d_{max} - x \tag{18}$$

Now it is time for numbers, and manager states that $X_{eff}(x) = 0.5$ is a point in a sigmoid curve like (3) for which $x = x_c = x_{max}/2$ and so $d = d_{max}/2$ as well. Instead of measuring d having an *a priori* physical reference (first choice), manager reads on meter that current consumption is around 20 kWh and the desired would be 15 kWh, and so sets $d_{max} = 10\,kWh$. This would mean a best-case energy saving of 25% that would be a good deal if the HMT works as hoped. Now, our model states that $x_{1,S,t_0}(d_1) = 5\,kWh$, $X_{eff,1,S,t_0} = 0.5$, and $\varepsilon = 0.1$ chosen arbitrarily as an initial guess to the slope of the curve (3). Moreover, a $\delta_{OEE} = 0.1$ is chosen to let the model to be considered fairly good if an error of around $\pm 1\,kWh$ acceptable in the predictions of the HMT. This can be assessed using (3) with $x = 5 \pm 1\,kWh$.

Coming back to the flowchart in Fig. 7, the HMT 1 of Fig. 8 is spawned (*SPAWN*), which consists only of its root. After setting $i = i + 1 = 1$ a STATS phase is invoked, which means in this particular initial case, checking the model with measurements against the condition $|OEE_{S,t_1}(x) - OEE_{I,t_0}(x)| > \delta_{OEE}$ with $OEE_{I,t_0}(x)$ being equal to the $OEE_{S,t_0}(x) = Q_{eff,S,t_0}(x) \overset{\text{def}}{=} X_{eff,S,t_0}(x) = 0.5$ because no previous *IMPROVE* phase outcome is available. If this is not the case, a new model and more well calibrated model on data should be used and so another *REFINE* of the root. Instead we suppose that the manager did fairly well on its first iteration having a good information, and so we should proceed to the next step towards the *IMPROVE* phase.

At this point the manager understands that she does not have yet any suitable model for the improvement action, as discussed in "Construction and definition of the OEE KPI: the HMT kernel" section. Due to the extreme simplicity of her current HMT model, it is now difficult to describe a suitable improvement action and to model a prediction on its effects. Thus, a new *REFINE* phase is needed immediately, and the model index is incremented by $n = n + 1 = 2$, as of the flowchart in Fig. 7. In this phase, the manager considers that the energy consumption is contributed by the sum of the energy used in the production line by machines, tools, and lights plus the energy used to keep the building facility comfortable for workers with heating systems. Being consumption a sum of two reasonably independent contributions, the parallel structure in Fig. 8 becomes the HMT 2 after this *REFINE 1* step. The goal $G1$ becomes $G1_P$ to denote a *parallel* structure, and the goals $G2$ and $G3$ can be interpreted as follows:

- **G2**. It the goal related to increment energy savings of the production line concerning machines, tools, and lights.
- **G3**. It is the goal related to the achievable energy saving in the thermal comfort of the building facility where workers act.

At this point, to manager's knowledge, it is again difficult to act on the side of the production line machinery, at least not in the short term, due to some complexity in this kind of intervention. More simple is to look first at the $G3$. Indeed, due to the parallel structure property, none of the sub-goals constitute a bottleneck: any improvement on one or the other will benefit the whole $G1_P$ (see *Parallel* case on table 3). To go on, manager attributes $OEE_{G2} = OEE_{G3} = 0.5$ having no other information. This provides a new starting point in the middle. However, the manager encounters difficulty here to provide some definitions both for x_{G2} and x_{G3}. In this case neither a *STATS* phase can be processed, but a tentative new *REFINE* step with $n = n + 1 = 3$ and $i = i + 1 = 2$.

This is the *REFINE 2* in Fig. 8, where manager thinks she has some good knowledge in transforming $G3$ into $G3_S$, a *series* of goals, namely $G4$ and $G5$ interpreted as:

- **G4**. It is the goal related to address energy savings while guaranteeing thermal comfort for workers in the productive premises.
- **G5**. It is the goal related to the achievable energy saving due to coping with thermal leaks that, in first approximation, are connected to the operations in the building facility, in particular opening of windows or doors during Winter.

This time a *series* structure has been the manager's choice, because this is a typical structure where trade-offs are considered. In this case, failing in the pursuing of $G4$, better comfort, might render ineffective any improvement towards the $G5$ and vice versa, so that one of the two objectives becomes the bottleneck on which to prioritise. *Series* seems a sound model according to the manager's belief.

With this refinement, posing $OEE_{G4} = OEE_{G5} = 0.5$, and $Q_{eff,G4} = A_{eff,G4} = Q_{eff,G5} = A_{eff,G5} = 1$ seems a suitable choice to keep things pretty simple.

Being the $G4$-$G5$ series in the condition $S2$ corresponding to $OEE_{G4} Q_{eff,G5} = OEE_{G5} = 0.5$ of Table 3, the improvement possibilities left with former positions are the following:

- $\Delta OEE_{G4} = 1 - OEE_{G4} = 0.5$
- $\Delta OEE_{G5} = 1 - OEE_{G5} = 0.5$

The manager therefore has two goals to turn his attention to. She first exploits her knowledge about $G5$. She knows that there are two openings in the building used for logistics operations. From a BIM model simulation, they know that each opening produces a loss of 0.5 kWh of thermal energy. Thus, acting on logistics procedures in order to use only one opening and closing the other would ideally save energy up to 0.5 kWh. This is a feasible and predictable improvement action. Starting from $OEE_{G5} = P_{eff,G5}(x_{G5,3,S,t_2}) = X_{eff,3,S,t_2} = 0.5$, we have to quantify again for the metric of this new $x(d)$, and so provide physical grounding. Manager knows from meters that the building on average consumes 3 kWh and decides to use again the simple set of equations (17) and (18) and the same sigmoid and ε as before. Again here, $x_{max} = d_{max}$ and $x_{min} = d_{min} = 0$ and $x = x_c = d_{max}/2$ and so $d = d_{max}/2$. Note that, from time to time and from each *REFINE* step, the choice on $X_eff(x(d))$ might change to fit a specific context. Here the case has been kept intentionally the simplest for brevity.

Now, it is assessed that $x_{max} = d_{max} = 3\,kWh$, meaning that an expected improvement of $0.5\,kWh$ would achieve a (circa) 33% of effectiveness change (both improving or worsening) from the central point $d(x_c) = 1.5\,kWh$.

Using the expression (3), $OEE_{G5,3,I,t_2} = X_{eff}(1.5 + 0.5) = 0.6753$, so using the series formula for OTE we obtain (see Table 3) $OTE_{G3_S} = min\left\{OEE_{G4}Q_{eff,G5}, OEE_{G4}\right\} = min\{0.5 \cdot 1, 0.6753\} = 0.5$.

No improvement expected? This is congruent with physical reality. Reducing losses will not directly produce a savings advantage until the amount of heat produced with other energy is not actually reduced. This will only happen, eventually, by acting on goal $G4$: this will make it easy to lower the heaters to the comfort temperature and save energy at the same time.

Indeed, if we come back to the $S2$ condition in Table 3, the improvement foreseen is exactly 0. But we now are in the case of "augmented improvement potential"; now the bottleneck of the series is on $G4$ and we must act on $G4$. All the improvements there achieved will go into a higher OTE_{G3_S} that will also affect positively OTE_{G1_P}, the whole.

The action on $G5$ is applied with an *APPLY* phase and the new *STATS* phase confirms that the model is valid (or not in general), with $i = i + 1 = 3$, according to Fig. 7.

Focusing on $G4$, the manager knows that the comfort can be reached if the temperature is kept at $21°C$. She also is told that for each increment of 1 degree there is an added consumption of $0.25\,kWh$. With a look at the current temperature on the thermostat it is read $22.5°C$. Thus, setting it back to $21°C$ will cut $0.375\,kWh$. By setting $x_{min} = d_{min} = 0$, $x_{max} = d_{max} = 0.75\,kWh$, $d(x_c) = 0.375\,kWh$, again with the same expressions (16) and (3), after the *APPLY* of the regulation action on the heating system, we must have (with $\varepsilon = 0.1$) $OEE_{G4,3,I,t_3} = X_{eff}(0.375 + 0.375) = 0.9$.

After applying the two improvements that follow,

$$\begin{aligned} OTE_{G3_S} &= min\left\{OEE_{G4}Q_{eff,G5}, OEE_{G4}\right\} \\ &= min\{0.9 \cdot 1, 0.6753\} = 0.6753 \end{aligned}$$

and

$$\begin{aligned} OTE_{G1_P} &= \frac{OTE_{G2} + OTE_{G3_S}}{2} \\ &= \frac{0.5 + 0.6753}{2} = 0.58765 \end{aligned}$$

what did we ultimately achieve? An increment $\Delta OTE_{G1} = 0.08765$ (for the whole system). Isn't it much? Yes it is, because the actual number is immaterial for the HMT that is based on constructivism. In addition, the actual quality of the HMT modelling made, and so the scale of the numbers as outcomes, has to be verified within the subsequent *STATS* phase. In any case, the MHMT has guided the manager towards improvement, by making all the (limited) knowledge and measurements available in a most effective way. We can say that MHMT conducted a maieutic action on the manager, which can be recorded, transferred, and learned, as well.

Related work and discussion

The practical viability and strength of the HMT and its meta structuring, namely the MHMT established in "The MHMT methodology against complexity" section, is built over the concept of self-similarity and fractal structuring.

The fractal vision and the self-similarity concept can be found sustained from examples and applications in manufacturing sector (Bonci et al., 2017a; Bonci et al., 2017b, 2018a, b; Bonci et al., 2018c, 2019a, b; Pirani et al., 2016; Suárez et al., 2013) and then mutuated to more human-centric processes like in the construction sector (Bonci et al., 2019; Carbonari et al., 2018; Carbonari et al., 2020; Naticchia et al., 2019; Pirani et al., 2018), the smart home (Diaconescu et al., 2016), in software engineering (Straneo & Amo, 2009), in transportation (Le Mortellec et al., 2013; Tchappi et al., 2020), in power management and smart grids (Howell et al., 2017; Frey et al., 2015). Recently, the same concept has been under the interest of the infrastructure and logistics management in health sector (Mazilu & Tundrea, 2021).

The HMT core application is in decision-making for continuous improvement, even in situations where low digitalization is available (Stadnicka et al., 2017). All the performance measurement based methods search for continuous improvement (Ravelomanantsoa et al., 2019), but digitalization is not always essential in view of recent studies that analyze its impact with respect to lean management and *Kaizen* (Anosike et.al., 2021). Currently, a keen research activity is indeed exploring the systematization of human dimension in holonic control architectures in order to make their scope and action more effective and holistic (Valette et al., 2021).

Widening the scope to the enterprise architecture (EA), MHMT is a promising tool, as it can cope with multidimensional business, economic, social, and ecological viewpoints so as to be able to represent respective concerns of stakeholders (Bernus et al., 2016). MHMT includes systems thinking approaches that increasingly often rely on enhanced interpretations and implementations of DTs (Bianconi et al., 2020; Hribernik et al., 2021). Moreover, the MHMT is a viable possibility in order to tackle the grand challenge of "living with complexity" for an enterprise seen as a cybernetic system of systems and its socio-technical decision making on the system-as-a-whole (Bernus et al., 2016).

As recalled in "Background and recall of the Holonic Management Tree technique" section for HMT, and then explained in particular for the MHMT in "The MHMT methodology against complexity" section, the holon concept is used here in a way still compliant with major nuances and implementations of holonic control systems architectures Barbosa et al. (2015), Cardin et al. (2018), Derigent et al. (2021), Indriago et al. (2016), Jimenez et al. (2017), Valckenaers (2018, 2020), Valette et al. (2021), and Piardi et al. (2021), but with a focus on the self-similar emergence structure of the part and the whole that are two realities stranded by the holon with different semantics. Holonic approach is agnostic with respect to the particular hierarchical level and the implied technologies. The unifying self-similarities of the HMT can range across the multidimensional and heterogeneous steps of a business project management model execution (Reijers, 2021), as envisioned for example by Bonci et al. (2019b).

Case studies

Beyond the research experiences conducted in the literature presented in the previous section, the HMT methodology and its evolution into MHMT has already been applied in two relevant case studies. An initial prototype of HMT was tested in the ENCORE project,[2], the results of which are available on the dedicated project page.[3] In this case, HMT represented the basic paradigm for the continuous improvement and testing of a building automation and renovation management. The experiment was conducted through the realisation of an appropriate Web interface for conducting the STATS and IMPROVE phases, which concern the HMT technique. For more details, and for lack of further space, we refer the reader to the available public documentation, in particular the two public deliverables ENCORE (2021, 2022).

A description of the paradigm adopted both for the implementation of the HMT and the Web interface is available in Pirani et al. (2023), which case study is exactly that of the ENCORE project.

With same basic HMT technology and methodology, but enhanced with the new MHMT additions, a case study on holistic management of food supply chain is undergoing experimental sessions in the ENOUGH project.[4] In this case study, the construction of the HMT is tested for the first time on the complex supply chain problem ranging from the global management of participants towards a common GHG (greenhouse gas) reduction commitment, to the local operations of a typical DCS (distributed control system). In this experiment, the interface with the MHMT is not only a Web interface, but also an MR (mixed reality) application, in which the user can mediate between the complexity of the (physical) environment and its digital representation and modelling (twin). With these means, the development of the MHMT follows a procedure similar to the one exposed in "An explicative example" section. A demonstration is currently under construction.[5] Public results on this part of the project will be available from the third quarter of 2025.

For both projects and case studies, the underlying technology and paradigm proposed for the implementation of HMT and MHMT is the Relational-model Multi-Agent System (RMAS) (Pirani et al. 2021, 2022, 2023; Stadnicka et al., 2023, 2020).

Limitations and future research directions

Although the HMT, completed with the MHMT layer proposed here, is promised as a general toolkit and framework, more systematic results have yet to be collected. In particular, the HMT, by its very conception, is able to achieve a good balance between local and global control, but its effects should be examined in more detail to compare it with other holonic and semi-hierarchical (holarchical) control architectures, as already attempted by Bendul and Blunck (2019). The use of HMT in the real management cases is destined to meet more mature practices in failure and improvement analysis. For example, Mokhtarzadeh et al. (2024) provide a literature review that should assist analysts in developing hybrid failure analysis methodologies that leverage the strengths of both proactive methodologies like failure mode and effects analysis (FMEA) and reactive methods such as root cause analysis (RCA) and fault tree analysis (FTA). HMT itself can be used as a new hybrid integrator of all these methodologies in its models. This aspect is the focus of ongoing research on HMT and has not yet been comprehensively addressed at present.

Cybernetics can provide a useful ground towards a systematic handling of artificial cognition, which is still an open problem, beyond HMT. Indeed, it is in the cybernetics community that one can find new useful frameworks that attempt

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[2] EU H2020 ENCORE: *ENergy aware BIM Cloud Platform in a COst-effective Building REnovation Context* Grant agreement ID: 820434, https://cordis.europa.eu/project/id/820434

[3] https://cordis.europa.eu/project/id/820434/results

[4] EU H2020 ENOUGH: European food chain supply to reduce GHG emissions by 2050, Grant agreement ID: 101036588, https://cordis.europa.eu/project/id/101036588, https://enough-emissions.eu/

[5] ENOUGH Demo 1 - Holistic supply chain management and control, https://enough-emissions.eu/demonstrator/demo-1-holistic-supply-chain-management-and-control/

Table 2 Systemic frameworks, methodologies, and technologies of cybernetics as key contributors to the complexities of I4.0/5.0

Roadmap for Cybernetics 5.0-compliant components to meet the complexities of Industry 4.0/5.0.

Concern	2024–2027	2028–2030
Industry 4.0/5.0 major generators of complexity in the period	Growing activity around the enabling technologies of the Asset Administration Shell (AAS) (Miny et al., 2023)	Cyber-Physical-Human Systems (CPHS) (Matthies et al., 2023; Valette et al., 2023; Trentesaux & Karnouskos, 2022). Cognitive DT and CPS (Ali et al., 2024)
	Distributed Ledger Technology & Cybersecurity (Nasrullah et al., 2022)	Addressing UN-SDGs, i.p. 5,7,8,9,11
	Integrating/upgrading IEC 61131 with IEC 61499 (Sehr et al., 2021)	Overall safety and security
	Supply chain management	Autonomic systems and agents
	Operator 4.0/5.0	Artificial General Intelligence
	Cloud to physical computation continuum and software defined networks (Huh & Hossain, 2021; Nguyen et al., 2022; Pham et al., 2023)	Responsible and trustworthy AI (Raikov et al., 2024)
	Harmonization and interoperability of the numerous reference architectures (Kaiser et al. 2023)	
Systemic framework	Model-Based Systems Engineering (MBSE) integrating cybernetics interpretation at different levels, from 0^{th} to 3^{rd} order	Pragmatic constructivism and pragmatic reductionism taken together
	Permeate the CPSoS vision with cybernetics purposeful loops	Increased systems thinking in the form of SE (systems engineering)
	Introduction of self-similarities in SoS including seamlessly humans and machines	Hybrid reality, as defined in Raikov and Pirani (2022a)
Methodology	A focus on Holonic Control Architectures (HCA)	Deeper automation of the MHMT, involving structural causal modelling, generative machine learning, and Causal Path Analysis
	HMT (Holonic Management Tree) as an instance of viable HCA	Mapping MHMT to the inherent recursiveness and completeness of the Viable System Model (VSM) towards Cyber-physical Viable System approach (Bonci et al., 2018b). Holonic interpretations of hybrid reality (Raikov & Pirani, 2022a, b)
	Simplified new plugins of the HMT kernel where Bayesian expressions provide subjectivity and variety, with more separability and easier inverse modelling for predictions	
	Quantitative System Dynamics (SD) for the HMT modelling	
	Improvement of OEE modelling and extension of the ISO 22400 methodology (Bonci et al., 2019b)	
Technology	Active database as event-based systems grounding HMT (Bonci et al., 2018c)	Full-fledged formal models of the full relational model (Pirani et al., 2022), aiming at self-rewriting logic
	Database-centric application interfaces (Pirani et al., 2023)	RMAS for autonomic computation (Bonci et al., 2019). Natural and sustainable computation for CPS and AI (Pirani et al., 2021)
	Runtime verification and Enforcement on IEC 61499 (Falcone et al., 2022)	Lingua Franca used in constructivism for holonic systems, in MBSE of distributed databases and CPSs (Lee et al., 2023; Lohstroh et al., 2021), where actors interaction creates deterministic reality (Hewitt, 2010; Menard et al., 2023; Lee, 2021)
	RMAS (relational-model Multi Agent Systems) for IEC 61499 (Bonci et al., 2020, 2021)	

to provide an effective formalisation of artificial cognition problems (Wang & Tunstel, 2019). The solution of such kind of problems are revolving around recursive structures (Jantsch, 2019), in a way very similar to the recursive patterns envisioned in the HMT.

In this article, the main objective is to thoroughly detail the methodology of MHMT after contextualising it as an important tool for Cybernetics 5.0 as a whole. The aim is therefore to let this article be an initial and primary reference for new research and experimentation planned in the near future. Our focus here is not so much on the implementation of MHMT as on its principles, as a technique rather than a technology. In fact, both Cybernetics 5.0 and MHMT can even be considered technology agnostic. At the extreme, MHMT could be implemented by a manager with just pen and paper.

The major limitations of MHMT-like applications today are the difficulties in their complete automation and digitization, particularly in the *IMPROVE*, *APPLY*, and *REFINE* phases. Automation is necessary when real-time control is required. Currently, the simplification brought by the MHMT cannot be used as a ready-to-eat tool, but rather as a methodology.

On the one hand, MHMT is an engineering methodology ready for the challenges of mitigating Black Swans through precautionary principles, as advocated by Taleb (Taleb et al., 2014), and of designing for the unexpected (Valckenaers & Van Brussel, 2015). On the other hand, MHMT has to address the difficulties of systematization for specific sectors, particularly for processes with a higher degree of automation as in Industry 4.0/5.0. These technological difficulties are mitigable in part if MHMT is combined with a pervasive database-driven technology that enables process mining activities for statistical collection and classification.

A deeper analysis has to involve the formulas at the basis of the computing of the OEE and OTE, starting from the expression (1) and through all the developed expressions and discussion in Bonci et al. (2019a). The formulas has to be considered just a first attempt, and they are not the core of the HMT concept, but only a first instance.

As seen in “The MHMT methodology against complexity” section, the concepts were discussed here without the need to explicitly recall the complete formulas on OTE and OEE found in the literature. The current formulas, available for example in Bonci et al. (2018c, 2019a), derive from an extension of an interesting attempt to generalize the OEE by Muthiah and Huang (2007) in manufacturing context. However, in the experiences conducted so far, we could spot many numerical and non-linear behavioural issues in them, which may limit the actual grasp and simplicity in their practical application.

The OTE/OEE expressions are to be considered a plug-in that here was defined as the *HMT kernel*. In future developments of MHMT, they can be surely improved and changed, to be adapted more easily and dynamically to in the context they are applied to. For example, some of their hard non-linearities could be avoided without losing overall modelling efficacy. Another interesting survey should be made in order to provide a Bayesian form to their expression, which could at the same time simplify their calculus and deepen their meaning and strength in the pragmatic constructivism that the HMT method puts forth.

Information security (or cybersecurity) aspects are also to be considered. The confidentiality of information circulating through the CPSoS superimposed on a problem as a whole, which the MHMT breaks down into more manageable holarchies, deserves careful consideration. These problems are currently appearing in case studies such as the ENOUGH project mentioned in the previous section.

The connection between cybernetics discipline as a whole and cybersecurity aspects in general has to be considered. An interesting proposal in this sense can be found in the work of Cernauskas and Kumiega (2022), but this theme needs more exploration and efforts to be developed up to a mature and practical stage.

Within the framework of the MHMT, in cases where a group of autonomous participants collaborate on a teleological objective, only a part of the information must remain public within certain levels of the holarchy. This requires specific layers of software protection, role-based access control, and other security issues. The holarchy is in this case a society of agents (human or artificial) which security and privacy has to be under due control and regulation. This problem is complementary to the principles of the MHMT, but fundamental for its practical implementations where as a societal network of holons is often implied, with inherent networking security requirements.

In the ENOUGH project, undergoing research is also addressing these issues with appropriate software security layers added to MHMT, along with means for confidentiality, trust, and reputation coming from the distributed technology framework (DLT), like the Blockchain, zero-knowledge proofs, self-sovereign identity systems, Runtime Verification and Enforcement (Spegni et al., 2023), and non-fungible tokens (Pirani et al., 2023).

An attempt is made in the following to provide a roadmap that frames the role of MHMT in the context of the foreseen developments of engineering methods and practices in the field of Industry 4.0 and 5.0. This roadmap is mostly a display, by means of Table 2, of how authors intend to organize future research in this field, although the additional hope is that the industrial informatics community will come together and support some of these same ambitions.

The first feature of the table (Table 2) is to show an estimate of which technology and problem components of I40/I50 are expected to impact most during the two periods covered by the roadmap. This constitutes the first row of the table.

The other rows contain correspondences to the first row about the scientific and technological activities to be performed at three different levels:

- at the systemic framework level, where several elements of systems thinking, cybernetics, systems of systems definitions, and model-based systems engineering convey their contribution;
- at the methodology level, where the essence of the HMT along with its foreseen improvements and extensions should act;
- at the technology level, as HMT is subject to many types of realisations and implementations, and the authors' primary choice is described, along with other valid results available in the engineering community.

Please note that the purpose of Table 2 is not to provide a systematic set of references to each of the items cited, but to indicate a perspective based on the contents discussed earlier in this paper, while at the same time providing some key references for the introduction to the topics mentioned therein, the treatment of which is beyond the scope and space of this paper.

Conclusion

With this paper, we had the opportunity to present a review of the issues that link the goals and problems of I4.0/I5.0 to the long-standing structure of work coming directly from cybernetics.

To this end, we first recalled the definitions proper to cybernetics, considering its most current development, which brings together in a transdisciplinary way the problems of the relationship between computer science and the humanities. The need for disciplinary integration stems from the latest developments in Industry 4.0, but is particularly present in the new ambitions of Industry 5.0.

With the definition of *Cybernetics 5.0*, we denoted a reconnection between the strong drifts of ultra-specialisation of engineering and the need for a recovery of a systemic but at the same time holistic vision. Incidentally, this a process and trend that has long been established in digital manufacturing and industry in general, both with the introduction of concepts such as CPSoS (cyber-physical systems of systems) and holonic architectures based on multi-agent systems.

The main substantive proposal was then articulated into three research questions that were addressed and discussed.

The RQ1 was asking for a modernized version of transdisciplinary cybernetics to be a valuable framework for I40/I50 against the increased difficulties of designing and controlling the complex socio-technical playground of current and future industrial practices. RQ1 was answered with the proposition of the Cybernetics 5.0 framework that has the potential to reunite modern cybernetics and current research in the operational and the informational management technologies of the I40/I50 as a transdisciplinary whole, by making a decisive relation with the problem of complexity of decision making, management and control.

The RQ2 asked wether the numerous efforts around promising holonic architectures would have any room for enrichment and improvement in order to comply with the proposed renovated cybernetics principles and visions. To this end, the holonic approach of the authors was reviewed and recalled to establish the HMT technique as a viable representative of holonic architectures, although it clearly can represent just one instance for the enforcement of the renewed link between cybernetics and the management problems involving CPS for I40/I50.

Finally, RQ3 was inquiring about which technologies are under investigation and test in the field of applications of the holonic methodology in the promoted strong coupling between holonics and Cybernetics 5.0. In this context, the MHMT constitutes a framework for the purposeful and organized collection of state-of-art efforts towards the new horizons envisioned for I40/I50. This required a detailed upgrade of the HMT technique into the MHMT. It consists in a systematic meta process that is candidate to fulfill the relevant technical and technological requirements of Cybernetics 5.0.

The thorough definition of MHMT, realized here for the first time, addresses a comprehensive definition of a systematic process that manages the meta level of HMT, relating to the refinement and synthesis of HMT itself, capable of continuously chasing the complex evolution of reality that a specific instance of HMT can only address locally in space and time.

The MHMT here proposed, is to be considered just a first tool for the challenges of the Cybernetics 5.0. There must be many alternatives coming from the joint endeavours of complexity theory, management practice, and engineering that will be put in comparison with MHMT for performance and efficiency. We can here mention the fast-and-frugal decision making (Hafenbrädl et al., 2016), the tools in nudge theory, the Viable System Model (Reynolds & Holwell, 2020), frameworks like Cynefin (Snowden, 2021) in complexity, adaptive operations research techniques, the HABA-MABA (De Winter & Dodou, 2014) and human factors (Bjurling et al., 2024), systems dynamics and systems thinking (Sterman, 2002). In the case of complexity, however, whatever methodology or technique is chosen, the golden rule is that none will be definitive. The no-free-lunch theorems can also be used to formalise this rule.

To the authors' knowledge, none of the existing methodologies can be directly compared with the MHMT, or at least an effort by the transdisciplinary systems engineering community should help to cover this effort. Thus the road to an assessment of the effectiveness and actual viability of the MHMT can be long. The authors have started real-field experimental sessions (see section 5.1) that will be reported in subsequent reports.

New perspectives and future work have been compiled in the form of a roadmap covering two increasingly challenging periods until the not-too-distant goal of 2030. The roadmap provided here has a dual purpose. The first is to show the authors' research intentions with respect to their perception of the major generators of complexity in the medium term in I40/I50. The second, is to link this activity to available advances in the scientific community, having clear a selection of the methodologies and technologies most likely to be able to show complementarity and synergy with MHMT and its implications in the context of Cybernetics 5.0.

Of course, both the roadmap and this discussion are not meant to be exhaustive, but to indicate a clear path and lessons learnt from experience in various research and innovation projects in industry and beyond.

Appendix A *IMPROVE* action reference chart

In this section, the long Table 3 describes the condition/action rules that are used to implement the performance improvement algorithm (*IMPROVE* phase of the HMT). Note that actions with OTE gain equal to 0 are still useful to move the system out of a not improvable situation and relative state conditions (see an example in "An explicative example" section). Any move in such a situation stores OTE's improvement potential for the next iterations of *IMPROVE*.

Notation remark: in order to keep the formulas in Table 3 in compact notation, O stands for OEE and Q stands for Q_{eff}. In the *Assembly*, Q_a is the Q_{eff} of head cell of the structure. In the *Expansion*, Q_e is the Q_{eff} of the head cell of the structure. See "Construction of the Structural Relation: the HMT structure" section and Fig. 6 for more insights.

Table 3 Conditional formulas for the computation of the *IMPROVE* phase

Parallel		$OTE = \frac{O_1 + O_2}{2}$	
Tag	Condition	*Improvement actions available*	*OTE gain*
P1	$\frac{O_1 + O_2}{2} \leq 1$	$\Delta O_1 = 1 - O_1$	$\Delta O_1/2$
		$\Delta O_2 = 1 - O_2$	$\Delta O_2/2$
Series		$OTE = min\{O_1 Q_2, O_2\}$	
Tag	Condition	*Improvement actions available*	*OTE gain*
S1	$O_1 Q_2 < O_2$	$\Delta O_1 = min\left\{\frac{O_2}{Q_2}, 1\right\} - O_1$	$\Delta O_1 Q_2$
		$\Delta Q_2 = min\left\{\frac{O_2}{O_1}, 1\right\} - Q_2$	$O_1 \Delta Q_2$
S2	$O_1 Q_2 = O_2$	$\Delta O_1 = 1 - O_1$	0
		$\Delta O_2 = 1 - O_2$	0
		$\Delta Q_2 = 1 - Q_2$	0
S3	$O_1 Q_2 > O_2$	$\Delta O_2 = O_1 Q_2 - O_2$	ΔO_2
Assembly		$OTE = Q_a min\left\{\frac{O_1}{k_1}, \frac{O_2}{k_2}, \frac{O_a}{Q_a}\right\}$	
Tag	*Condition*	*Improvement actions available*	*OTE gain*
A1	$\frac{O_1}{k_1} < \frac{O_2}{k_2} < \frac{O_a}{Q_a}$	$\Delta O_1 = min\left\{\frac{k_1}{k_2} O_2, 1\right\} - O_1$	$\frac{\Delta O_1 Q_a}{k_1}$
		$\Delta O_2 = min\left\{\frac{k_2}{Q_a} O_a, 1\right\} - O_2$	0
		$\Delta k_2 = min\left\{\frac{k_1 O_2 - k_2 O_1}{O_1 + O_2}, k_1\right\}$	$Q_a\left[min\left\{\frac{O_1}{k_1 - \Delta k_2}, \frac{O_2}{k_2 + \Delta k_2}, \frac{O_a}{Q_a}\right\}\right] - \frac{O_1}{k_1}$
		$\Delta Q_a = min\left\{k_2 \frac{O_a}{O_2}, 1\right\} - Q_a$	$(Q_a + \Delta Q_a)\, min\left\{\frac{O_1}{k_1}, \frac{O_a}{\Delta Q_a + \Delta Q_a}\right\} - \frac{Q_a O_1}{k_1}$
A2	$\frac{O_1}{k_1} = \frac{O_2}{k_2} < \frac{O_a}{Q_a}$	$\Delta O_1 = min\left\{k_1 \frac{O_a}{Q_a}, 1\right\} - O_1$	0
		$\Delta O_2 = min\left\{k_2 \frac{O_a}{Q_a}, 1\right\} - O_2$	0
		$\Delta Q_a = min\left\{\frac{O_a}{O_1 + O_2}, 1\right\} - Q_a$	$(Q_a + \Delta Q_a) min\left\{\frac{O_1}{k_1}, \frac{O_a}{Q_a + \Delta Q_a}\right\} - \frac{Q_a O_1}{k_1}$

Table 3 continued

Tag	*Condition*	*Improvement actions available*	*OTE gain*
A3	$\frac{O_1}{k_1} < \frac{O_2}{k_2} = \frac{O_a}{Q_a}$	$\Delta O_1 = min\left\{\frac{k_1}{k_2}O_2, k_1\frac{O_a}{Q_a}, 1\right\} - O_1$	$\frac{\Delta O_1 Q_a}{k_1}$
		$\Delta k_2 = min\left\{\frac{k_1 O_2 - k_2 O_1}{O_1 + O_2}, k_1\right\}$	$Q_a\left[min\left\{\frac{O_1}{k_1 - \Delta k_2}, \frac{O_2}{k_2 + \Delta k_2} \frac{O_a}{Q_a}\right\} - \frac{O_1}{k_1}\right]$
		$\Delta Q_a = min\left\{k_1\frac{O_a}{O_1}, \frac{k_2}{O_2}, 1\right\} - Q_a$	$(Q_a + \Delta Q_a)min\left\{\frac{O_1}{k_1}, \frac{O_a}{Q_a + \Delta Q_a}\right\} - \frac{Q_a O_1}{k_1}$
A4	$\frac{O_1}{k_1} < \frac{O_a}{Q_a} < \frac{O_2}{k_2}$	$\Delta O_1 = min\left\{k_1\frac{O_a}{Q_a}, 1\right\} - O_1$	$\frac{\Delta O_1 Q_a}{k_1}$
		$\Delta k_2 = min\left\{k_1 - O_1\frac{Q_a}{O_a}, O_2\frac{Q_a}{O_a} - k_2, k_1\right\}$	$Q_a\left[min\left\{\frac{O-1}{k_1 - \Delta k_2}, \frac{O_2}{k_2 + \Delta k_2}, \frac{O_a}{Q_a}\right\} - \frac{O_1}{k_1}\right]$
		$\Delta O_a = min\left\{\frac{O_2 Q_a}{k_2}, 1\right\} - O_a$	0
		$\Delta Q_a = min\left\{k_1\frac{O_a}{O_1}, \frac{k_2}{O_2}, 1\right\} - Q_a$	$(Q_a + \Delta Q_a)min\left\{\frac{O_1}{k_1}, \frac{O_a}{Q_a + \Delta Q_a}\right\} - \frac{Q_a O_1}{k_1}$
A5	$\frac{O_1}{k_1} = \frac{O_a}{Q_a} < \frac{O_2}{k_2}$	$\Delta O_1 = min\left\{\frac{k_1}{k_2}O_2, 1\right\} - O_1$	0
		$\Delta k_2 = min\left\{\frac{k_1 O_2 - k_2 O_1}{O_1 + O_2}, \frac{Q_a}{O_a}O_2 - k_2, k_1\right\}$	0
		$\Delta O_a = \frac{O_2 Q_a}{k_2} - O_a$	0
		$\Delta Q_a = min\left\{\frac{k_2}{O_2}, 1\right\} - Q_a$	0
A6	$\frac{O_2}{k_2} < \frac{O_1}{k_1} < \frac{O_a}{Q_a}$	$\Delta O_1 = min\left\{\frac{k_1 O_a}{Q_a}, 1\right\} - O_1$	0
		$\Delta O_2 = min\left\{\frac{k_2}{k_1}O_1, 1\right\} - O_2$	$\frac{\Delta O_2 Q_a}{k_2}$
		$\Delta k_1 = min\left\{\frac{k_2 O_1 - k_1 O_2}{O_1 + O_2}, k_2\right\}$	$Q_a\left[min\left\{\frac{O_1}{k_1 + \Delta k_1}, \frac{O_2}{k_2 - \Delta k_1}, \frac{O_a}{Q_a}\right\} - \frac{O_2}{k_2}\right]$
		$\Delta Q_a = min\left\{\frac{k_1 O_a}{O_1}, 1\right\} - Q_a$	$(Q_a + \Delta Q_a)min\left\{\frac{O_2}{k_2}, \frac{O_a}{Q_a + \Delta Q_a}\right\} - \frac{Q_a O_2}{k_2}$

Table 3 continued

Tag	*Condition*	*Improvement actions available*	*OTE gain*
A7	$\frac{O_2}{k_2} < \frac{O_1}{k_1} = \frac{O_a}{Q_a}$	$\Delta O_1 = min\left\{\frac{k_1 O_a}{Q_a}, 1\right\} - O_1$	0
		$\Delta O_2 = min\left\{\frac{k_2}{k_1} O_1, 1\right\} - O_2$	$\frac{\Delta O_2 Q_a}{k_2}$
		$\Delta k_1 = min\left\{\frac{k_2 O_1 - k_1 O_2}{O_1 + O_2}, k_2\right\}$	$Q_a\left[min\left\{\frac{O_1}{k_1 + \Delta k_1}, \frac{O_2}{k_2 - \Delta k_1}, \frac{O_a}{Q_a}\right\} - \frac{O_2}{k_2}\right]$
		$\Delta Q_a = min\left\{\frac{k_2 O_a}{O_2}, \frac{k_1}{O_1}, 1\right\} - Q_a$	$(Q_a + \Delta Q_a) min\left\{\frac{O_2}{k_2}, \frac{O_a}{Q_a + \Delta Q_a}\right\} - \frac{Q_a O_2}{k_2}$
A8	$\frac{O_2}{k_2} < \frac{O_a}{Q_a} < \frac{O_1}{k_1}$	$\Delta O_2 = min\left\{k_2 \frac{O_a}{Q_a}, 1\right\} - O_2$	$\frac{\Delta O_2 Q_a}{k_2}$
		$\Delta k_1 = min\left\{k_2 - \frac{Q_a}{O_a} O_2, \frac{Q_a}{O_a} O_1 - k_1, k_2\right\}$	$Q_a\left[min\left\{\frac{O_1}{k_1 + \Delta k_1}, \frac{O_2}{k_2 - \Delta k_1}, \frac{O_a}{Q_a}\right\} - \frac{O_2}{k_2}\right]$
		$\Delta O_a = \frac{O_a O_1}{k_1} - O_a$	ΔO_a
		$\Delta Q_a = min\left\{\frac{k_2 O_a}{O_2}, \frac{k_1}{O_1}, 1\right\} - Q_a$	$(Q_a + \Delta Q_a) min\left\{\frac{O_2}{k_2}, \frac{O_a}{Q_a + \Delta Q_a}\right\} - \frac{Q_a O_2}{k_2}$
A9	$\frac{O_2}{k_2} = \frac{O_a}{Q_a} < \frac{O_1}{k_1}$	$\Delta O_2 = min\left\{\frac{k_2}{k_1} O_1, 1\right\} - O_2$	0
		$\Delta k_1 = min\left\{\frac{k_2 O_1 - k_1 O_2}{O_1 + O_2}, \frac{Q_a}{O_a} O_1 - k_1, k_2\right\}$	0
		$\Delta O_a = \frac{O_a O_1}{k_1} - O_a$	ΔO_a
		$\Delta Q_a = min\left\{\frac{k_1}{O_1}, 1\right\} - Q_a$	0
A10	$\frac{O_a}{Q_a} < \frac{O_1}{k_1} < \frac{O_2}{k_2}$	$\Delta O_1 = min\left\{\frac{k_1}{k_2} O_2, 1\right\} - O_1$	0
		$\Delta k_1 = min\left\{\frac{Q_a O_1}{O_a} - k_1, k_2 - Q_a O_2, k_2\right\}$	0
		$\Delta k_2 = min\left\{\frac{k_1 O_2 - k_2 O_1}{O_1 + O_2}, k_1\right\}$	0
		$\Delta O_a = \frac{Q_a O_1}{k_1} - O_a$	ΔO_a

Table 3 continued

Tag	*Condition*	*Improvement actions available*	*OTE gain*
A11	$\frac{O_a}{Q_a} < \frac{O_1}{k_1} = \frac{O_2}{k_2}$	$\Delta O_1 = min\left\{\frac{k_1}{Q_a}, 1\right\} - O_1$	0
		$\Delta O_2 = min\left\{\frac{k_2}{Q_a}, 1\right\} - O_2$	0
		$\Delta k_1 = \left\{\frac{Q_a O_1}{O_a} - k_1, k_2 - Q_a O_2, k_2\right\}$	0
		$\Delta k_2 = \left\{\frac{Q_a O_2}{O_a} - k_2, k_1 - Q_a O_1, k_1\right\}$	0
		$\Delta O_a = \frac{Q_a O_1}{k_1} - O_a$	ΔO_a
A12	$\frac{O_a}{Q_a} < \frac{O_2}{k_2} < \frac{O_1}{k_1}$	$\Delta O_2 = min\left\{\frac{k_2}{k_1} O_1, 1\right\} - O_2$	0
		$\Delta k_1 = min\left\{\frac{k_2 O_1 - k_2 O_2}{O_1 + O_2}, k_2\right\}$	0
		$\Delta k_2 = min\left\{\frac{Q_a O_2}{O_a} - k_2, k_1 - Q_a O_1, k_1\right\}$	0
		$\Delta O_a = \frac{Q_a O_2}{k_2} - O_a$	ΔO_a
A13	$\frac{O_1}{k_1} = \frac{O_2}{k_2} = \frac{O_a}{Q_a}$	$\Delta O_1 = min\left\{\frac{k_1}{Q_a}, 1\right\} - O_1$	0
		$\Delta O_2 = min\left\{\frac{k_2}{Q_a}, 1\right\} - O_2$	0
		$\Delta O_a = 1 - O_a$	0
		$\Delta Q_a = min\left\{\frac{k_1}{O_1}, \frac{k_2}{O_2}, 1\right\} - Q_a$	0
Expansion		$OTE = k_1 Q_1\, min\left\{\frac{O_1}{k_1 Q_1}, O_e\right\} + k_2 Q_2\, min\left\{\frac{O_2}{k_2 Q_2}, O_e\right\}$	
Tag	*Condition*	*Improvement actions available*	*OTE gain*
E1	$\frac{O_1}{k_1 Q_1} < O_e \ and\ \frac{O_2}{k_2 Q_2} < O_e$	$\Delta O_1 = min\,\{k_1 O_e Q_1, 1 - O_2\} - O_1$	ΔO_1
		$\Delta O_2 = min\,\{k_2 O_e Q_2, 1 - O_1\} - O_2$	ΔO_2
		$\Delta k_1 = k_2 - \frac{O_2}{O_e Q_2}$	0
		$\Delta k_2 = k_1 - \frac{O_1}{O_e Q_1}$	0

Table 3 continued

Tag	*Condition*	*Improvement actions available*	*OTE gain*
E2	$\frac{O_1}{k_1Q_1} < O_e and\ O_e < \frac{O_2}{k_2Q_2}$	$\Delta O_1 = min\,\{k_1O_eQ_1, 1 - k_2O_eQ_2\} - O_1$	ΔO_1
		$\Delta k_2 = min\left\{k_1 - \frac{O_1}{O_eQ_1}, \frac{O_2}{O_eQ_2} - k_2, \frac{1-O_1}{O_eQ_2} - k_2\right\}$	$\Delta k_2O_eQ_2$
		$\Delta O_e = min\left\{\frac{O_2}{k_2Q_2}, \frac{1-O_1}{k_2Q_2}, 1\right\} - O_e$	$k_2\Delta O_eQ_2$
		$\Delta Q_2 = min\left\{\frac{O_2}{k_2O_e}, \frac{1-O_1}{k_2O_e}, 1\right\} - Q_2$	$k_2O_e\Delta Q_2$
E3	$\frac{O_1}{k_1Q_1} < O_e\ and\ \frac{O_2}{k_2Q_2} = O_e$	$\Delta O_1 = min\,\{k_1O_eQ_1, 1 - O_2\} - O_1$	ΔO_1
		$\Delta O_2 = 1 - O_1 - O_2$	0
		$\Delta k_2 = \left\{\frac{1-O_1}{O_eQ_2} - k_2, k_1\right\}$	0
		$\Delta O_e = \left\{\frac{1-O_1}{k_2Q_2}, 1\right\} - O_e$	0
		$\Delta Q_2 = \left\{\frac{1-O_1}{k_2O_e}, 1\right\} - Q_2$	0
E4	$O_e < \frac{O_1}{k_1Q_1}\ and\ \frac{O_2}{k_2Q_2} < O_e$	$\Delta O_2 = min\,\{k_2O_eQ_2, 1 - k_1O_eQ_1\} - O_2$	ΔO_2
		$\Delta k_1 = min\left\{k_2 - \frac{O_2}{O_eQ_2}, \frac{O_1}{O_eQ_1} - k_1, \frac{1-O_2}{O_eQ_1} - k_1\right\}$	$\Delta k_1O_eQ_1$
		$\Delta O_e = min\left\{\frac{1-O_2}{k_1Q_1}, \frac{O_1}{k_1Q_1}, 1\right\} - O_e$	$k_1\Delta O_eQ_1$
		$\Delta Q_1 = min\left\{\frac{O_1}{k_1O_e}, \frac{1-O_2}{k_1O_e}, 1\right\} - Q_1$	$k_1O_e\Delta Q_1$
E5	$O_e < \frac{O_1}{k_1Q_1}\ and\ O_e < \frac{O_2}{k_2Q_2}$	$and\ Q_1 \geq Q_2; \Delta k_1 = min\left\{\frac{O_1}{O_eQ_1} - k_1, k_2\right\}$	$\Delta k_1O_e(Q_1 - Q_2)$
		$and\ Q_1 \leq Q_2; \Delta k_2 = min\left\{\frac{O_2}{O_eQ_2} - k_2, k_1\right\}$	$\Delta k_2O_e(Q_2 - Q_1)$
		$\Delta O_e = min\left\{\frac{O_1}{k_1Q_1} - O_e, \frac{O_2}{k_2Q_2} - O_e, 1 - O_e\right\}$	$\Delta O_e(k_1Q_1 + k_2Q_2)$
		$\Delta Q_1 = min\left\{\frac{O_1}{k_1O_e} - Q_1, 1 - Q_1\right\}$	$k_1O_e\Delta Q_1$
		$\Delta Q_2 = min\left\{\frac{O_2}{k_2O_e} - Q_2, 1 - Q_2\right\}$	$k_2O_e\Delta Q_2$

Table 3 continued

Tag	*Condition*	*Improvement actions available*	*OTE gain*
E6	$O_e < \frac{O_1}{k_1 Q_1}$ *and* $\frac{O_2}{k_2 Q_2} = O_e$	$\Delta O_2 = 1 - O_2$	0
		$and\ Q_1 \geq Q_2; \Delta k_1 = min\left\{\frac{O_1}{O_e Q_1} - k_1, k_2\right\}$	$\Delta k_1 O_e (Q_1 - Q_2)$
		$\Delta O_e = min\left\{\frac{O_1}{k_1 Q_1} - O_e, 1 - O_e\right\}$	$k_1 \Delta O_e Q_1$
		$\Delta Q_1 = min\left\{\frac{O_1}{k_1 O_e} - Q_1, 1 - Q_1\right\}$	$k_1 O_e \Delta Q_1$
		$\Delta Q_2 = 1 - Q_2$	0
E7	$\frac{O_1}{k_1 Q_1} = O_e$ *and* $\frac{O_2}{k_2 Q_2} < O_e$	$\Delta O_1 = 1 - O_1$	0
		$\Delta O_2 = min\{k_2 O_e Q_2, 1 - O_1\} - O_2$	ΔO_2
		$\Delta k_1 = k_2 - \frac{O_2}{O_e Q_2}$	0
		$\Delta O_e = 1 - O_e$	0
		$\Delta Q_1 = 1 - Q_1$	0
E8	$\frac{O_1}{k_1 Q_1} = O_e$ *and* $O_e < \frac{O_2}{k_2 Q_2}$	$\Delta O_1 = 1 - O_1$	0
		$and\ Q_1 \leq Q_2; \Delta k_2 = min\left\{\frac{O_2}{O_e Q_2} - k_2, k_1\right\}$	$\Delta k_2 O_e (Q_2 - Q - 1)$
		$\Delta O_e = min\left\{\frac{O_2}{k_2 Q_2} - O_e, 1 - O_e\right\}$	$k_2 \Delta O_e Q_2$
		$\Delta Q_1 = 1 - Q_1$	0
		$\Delta Q_2 = min\left\{\frac{O_2}{k_2 O_e} - Q_2, 1 - Q_2\right\}$	$k_2 O_e \Delta Q_2$
E9	$\frac{O_1}{k_1 Q_1} = O_e$ *and* $\frac{O_2}{k_2 Q_2} = O_e$	$\Delta O_1 = 1 - O_1$	0
		$\Delta O_2 = 1 - O_2$	0
		$\Delta O_e = 1 - O_e$	0
		$\Delta Q_1 = 1 - Q_1$	0
		$\Delta Q_2 = 1 - Q_2$	0

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