Science for Robot Policy: advancing robotics policy through EU's science for policy approach

Fosch Villaronga, E.; Shaffique, M.R.; Schwed Shenker, M.; Mut Piña, A.; Hof, S. van der; Custers, B.H.M.

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Advancing robotics policy through the EU science for policy approach

Eduard Fosch-Villaronga *, Mohammed Raiz Shaffique, Marie Schwed-Shenker, Antoni Mut-Piña, Simone van der Hof, Bart Custers

eLaw—Center for Law and Digital Technologies, University of Leiden, Leiden, Netherlands

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A B S T R A C T

The rapid advancement of service robotics has outpaced regulatory frameworks, leading to gaps and inconsistencies that hinder effective governance. While evidence-based policymaking is well-established in health and consumer protection fields, robotics regulation remains fragmented and reactive. This paper proposes Science for Robot Policy, a structured, evidence-driven model that bridges the disconnect between robotics innovation and regulatory adaptation. Using a Constructive Research Approach, the model integrates scientific experimentation, stakeholder engagement, and knowledge brokering to generate policy-relevant data and transform it into actionable regulatory insights. The model follows a five-step process, beginning with risk identification and prioritization, followed by controlled experimentation in simulators, testing zones, living labs, and real-world markets. The ambition is that insights generated are then translated into policy-relevant information and further refined into knowledge for policymakers, ensuring that empirical evidence informs that robotics regulation is dynamic, anticipatory, and informed. This approach contributes to ongoing discussions on science-for-policy methodologies and fosters iterative regulatory refinement in service robotics. If successful, such a model could allow policymakers to address emerging risks proactively, reduce regulatory uncertainty, enhance user safety, and promote responsible robotics innovation by embedding scientific insights into the policy cycle.

1. Introduction

Narratives of transformative economic and social progress have propelled the rapid development of robot technologies across various industries. From logistics, farming, and fire operations to the most intimate spheres of our lives, including surgery, therapy, or sex, the field of robotics promises to augment human capabilities and revolutionize how we live and work (Riek, 2017; Dupont et al., 2021; Jecker, 2021; Bogue, 2021; Martin et al., 2022). However, the rapid pace of technological innovation usually masks its impact on society, which is often more concerned about technology's practical benefits than assessing its negative implications (Borenstein et al., 2018; Carr, 2020). This velocity also outpaces the development of comprehensive legal frameworks that can adequately frame these developments, creating opportunities for companies to operate in fragmented legal spaces where enforcement is limited. In the context of robotics, industries may engage in practices prioritizing short-term gains over long-term ethical or legal considerations such as privacy, algorithmic bias, responsibility, and, most importantly, safety (Turkle, 2011).

A particularly underexposed area of technology is that of service robotics (Fosch-Villaronga, 2015; Canal et al., 2017; Asgharian et al., 2022). Unlike industrial or medical robots, service robots perform helpful tasks for people interacting directly with them. Typical examples are a robotic vacuum cleaner or a humanoid robot that gives you directions in a museum or at the airport (Lai and Tsai, 2018; Lee, 2021). As with any new technology, when these robots first appeared in labs or universities, there was no immediate need to regulate them. From a legal certainty perspective, this was not very problematic: since there were already many pieces of legislation for 'similar' technologies, such as machinery or toys, and for related issues, such as safety, data protection, or research ethics (Brownsword, 2008). This resulted in robot safeguards scattered across different pieces of legislation under different

* Corresponding author.
E-mail addresses: e.fosch.villaronga@law.leidenuniv.nl (E. Fosch-Villaronga), m.r.shaffique@law.leidenuniv.nl (M.R. Shaffique), m.schwed.shenker@law.leidenuniv.nl (M. Schwed-Shenker), a.mut.pina@law.leidenuniv.nl (A. Mut-Piña), s.van.der.hof@law.leidenuniv.nl (S. van der Hof), b.h.m.custers@law.leidenuniv.nl (B. Custers).

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nomenclatures or legal categories (i.e., products, toys, machinery). However, as this legislation was enacted at a time when robots did not exist, these issues (i.e., safety, data protection) were unevenly or only partially covered (Fosch-Villaronga, 2019; Salvini et al., 2021; Boada et al., 2021).

Soon, technology capabilities advanced, as did the contexts in which these new robots were employed. What changed the most was that instead of performing dangerous operations in factories, these robots interacted closely with humans (Breazeal et al., 2016). It was at that time that scholars and industry realized that safety machinery standards were generic and lacked concrete guidance on how to apply them to new developments, but also, most importantly, that they ensured safety by separating the robot from the human operator (e.g., in a car factory robots are caged separated from the workers), something that cannot be really done if robots are specifically intended to interact closely with humans (Jacobs and Virk, 2014; Fosch-Villaronga, 2015). It was then that the industry gathered to discuss and create a new standard, ISO 13482:2014, which was the first to establish safety requirements for personal care robots, a type of service robot that would comply with, at the time, the Machinery Directive within the New Legislative Framework.[1] However, this standard lacks important definitions, such as what personal care means (Fosch-Villaronga, 2016), and contains unclear categories, so it was not always clear which robots were covered by the standard (Fosch-Villaronga and Roig, 2017). At the technical and core safety level, it lacks adequate security requirements e.g., in relation to gender (Fosch-Villaronga and Drukarch, 2023; Forgas-Coll et al., 2023)

The lack of evidence-based information on the impact of new technologies on users is one reason for the scarcity of adequate interventions (Custers et al., 2008). These dissonances are unsurprising in standardization practices, as these processes are designed to serve industry interests and may lack effective user representation (Mattli, 2001; Bhimani et al., 2019). In addition to legitimacy issues around transparency and public interest, standards also face accountability issues given their usually non-binding nature and the limited mechanisms to oversee the validity of the content they define (Leenes et al., 2017; Fosch-Villaronga and Golia Jr., 2019). For instance, ISO/TR 23482–1:2020, which developed safety-related test methods to implement ISO 13482:2014, states that test methods still need to be widely implemented or evaluated.[2]

While other sectors, such as chemicals, food or pharmaceuticals, have evidence-based policies that translate policy goals into practical guidance, these frameworks are not yet in place for robotics. In this article, we, therefore, present a model for "Science for Robot Policy," a stepping stone in ideating practical ways to link robot experimentation to the policy cycle to help overcome the information asymmetries that jeopardize the efficiency of the regulation-making process, give end-users a voice, and shed light on what needs regulatory attention for adequate robot governance from an evidence-based perspective. Drawing on the EU's extensive experience in using scientific evidence for policy making in health, environment, research, consumer protection and digital policy (Šucha and Sienkiewicz, 2020), recent advances in methods such as anticipatory regulation and a strong push from the EU AI Act (AIA) for stakeholder participation in standardization activities, this article explores the application of the 'science for policy' paradigm in the field of robotics and outlines a roadmap for generating policy-relevant data to support policy changes in robotics.

In short, the aim of this paper is to work out a model capable of generating evidence-based data that could progressively be interpreted, validated, and contextualized in a way that makes it actionable for different audiences. If successful, this model will advance research on the use of science for robot policy and open avenues towards an evidence-based regulatory model for robots in the EU that guides rather than catches up with robot (r)evolution and is more attuned to societal needs and fundamental rights. The model has been designed using Constructive Research Methods (CRM), a research procedure for producing innovative constructions (Lehtiranta et al., 2015). CRM has barely been used systematically to improve the regulatory process, which reinforces the novelty of the approach followed in the present work.

This paper is structured as follows. Section 2 situates the discussion and provides certain background information needed to understand the overall purpose of this paper, especially regarding the legal framework and policy making process of service robots. Section 3 summarizes the methodological technique used. Sections 4 through 8 present "Science for Robot Policy," a working model capable of overcoming the main regulatory issues present in the domain of service robotics. Section 9 presents conclusions.

2. Background information

2.1. ISO and the law

ISO is an independent, non-governmental international organization, aimed to ensure safe, reliable, and high quality products and services to the general population across the world.[3] ISO plays a key role in shaping safety and performance standards globally, within the EU and beyond, because its guidelines are frequently adopted or referenced by many jurisdictions including the EU, the United States, Japan, and Canada, demonstrating a shared reliance on technical expertise and international benchmarks. ISO presents four key principles they follow in each standard development: respond to a request made by stakeholders for a new need in the market, base their standards on global experts under technical committees, develop these standards through a multi-stakeholder process, and make sure to take all comments into account when finalizing the standard (*ISO - What We Do*, 2025). These principles reflect a commitment to transparency, inclusivity, and scientific rigor. ISO explicitly supports an evidence-based approach to policy making, stating in its *Standards and Public Policy Toolkit* that "policy making should be evidence based. Policies and regulations should be based on the best available data and scientific expertise" (ISO, 2021, p.13). This affirms ISO's alignment with the broader goals of evidence-informed regulation, particularly relevant in rapidly evolving technological domains such as robotics.

ISO provides 3 types of standards organized by hierarchy:

- Type-A (basic safety standards) - giving basic concepts, principles for design, and general aspects that can be applied to machinery;
- Type-B (generic safety standards) - dealing with one safety aspect or one type of safeguard that can be used across a wide range of machinery;
- Type-C (machine safety standards) - dealing with detailed safety requirements for a particular machine or group of machines.

From the perspective of EU law, ISO standards are relevant as they can become 'harmonised standards', i.e., standards adopted by European Standardization Organisations based on a request of the European Commission for applying EU law (Regulation (EU) No 1025/2012, Article 2). Essentially, several EU legal instruments, such as the Machinery Directive (Directive 2006/42/EC), Medical Devices Regulation (Regulation (EU) 2017/745) and the Artificial Intelligence Act

[1] The New Legislative Framework (NLF) establishes the legal foundation for placing products on the market. Products that comply with harmonised European standards (such as ISO 13482:20214) are presumed to meet the essential legal requirements - in this case the Machinery Regulation. This simplifies the compliance process. *See* more at https://single-market-economy.ec.europa.eu/single-market/goods/new-legislative-framework_en.

[2] *See* https://www.iso.org/standard/71564.html.

[3] *See* https://www.iso.org/developing-standards.html.

(Regulation (EU) 2024/1689, n.d.), recognize that products and services manufactured in accordance to respective harmonised standards provide a presumption of conformity that they comply with the given EU law.[4] This 'presumption of conformity' of harmonised standards is one of the primary reasons why these standards are seen as part of EU law (*James Elliott Construction Limited v Irish Asphalt Limited*, 2016) and as de facto binding (*Fra.bo SpA v Deutsche Vereinigung des Gas- und Wasserfaches eV (DVGW) - Technisch-Wissenschaftlicher Verein*, 2012). Over the years, many standards including those from international standardization bodies, such as ISO, have been adopted as harmonised standards. Apart from enabling manufacturers to show regulatory compliance, these standards also play an important role in prescribing safety considerations to be incorporated.

However, such harmonised standards have often been criticised for not having adequate participation of civil society during the standard making process, and for privatising important matters that ought to be dealt with by lawmakers (Ducato, 2023). This is because, although risk-based approaches presuppose that evidence can be used for normative purposes, these are debatable given the lack of evidence used in the creation of norms and that sometimes the risks "are not scientifically measurable threats of physical harm but threats of human rights violations which are difficult to quantify" (Grozdanovski and De Cooman, 2022). This makes it difficult, if not impossible, to operationalize that knowledge-for-policy ideal. However, the regulation 1025/2012 explains in Annex II, Art. 4 e) iii), specifications for ICT should be based on advanced scientific and technological developments and operationalizing models that do so are needed.[5]

2.2. The EU science for policy framework

Evidence-based policymaking (EBPM) is the phenomenon of using evidence to design and implement law and policy (Pflücke, 2024). It is based on the rationale that policymaking should focus on objectivity and rational thinking and not be influenced by external considerations such as political interests. This distinction refers specifically to undue influence from narrow political or commercial interests, not to stakeholder engagement. Meaningful consultation with a wide range of actors — including researchers, developers, users, and civil society — can help evidence be relevant, robust, and grounded in practice. Given current lobbying structures, this approach is hard (Mattli, 2001; Parkhurst, 2017; Justo-Hanani, 2022). Nevertheless, the European Commission (EC) has a 'Better Regulation Agenda,' which consists of guidelines and a toolbox to ground EU policy making in the best available evidence (EC, n.d.-a, EC, n.d.-b, EC, 2021). To this end, the EC created the online platform 'Knowledge 4 Policy' to leverage scientific evidence to support policymaking.[6] Using evidence to guide policy decisions has been the EU's approach for more than two decades, leading to more effective policies, improved decision-making processes and enhanced public trust (Pflücke, 2024). This permeates several areas of EU law, including asylum law (Nicolosi, 2022), environmental law (Khadim and Van Eijken, 2022) and competition law (Sluijs, 2022).

An area related to robotics where the evidence-based mechanism has been used is EU consumer protection law. There are power imbalances between the economically vulnerable consumers and powerful and market-controlling businesses (Ouyang, 2024). The European Commission collects scientific evidence through applied empirical methods, including consumer surveys, behavioral research, market monitoring, and market studies. Although these methods are often categorized as gray literature, they follow systematic, data-driven approaches and are recognized as scientifically valid within the framework of evidence-informed policymaking (EC, n.d.-c). Thanks to the evidence provided by the European Commission, EU consumer law has evolved over the years to remedy imbalances such as the weaker bargaining power of consumers (*Horațiu Ovidiu Costea v SC Volksbank România SA*, 2015) by enacting regulatory measures such as the Unfair Terms in Consumer Contracts Directive in 1993 (Council Directive 93/13/EEC). In the same vein, the Financial Services Distance Contracts Directive (Directive (EU) 2023/2673) introduces further protection by explicitly prohibiting the use of dark patterns, which are behavioral design practices aimed at manipulating consumer behavior (Zard and Sears, 2023). This directive is an example of EBPM that relies on behavioral research to protect consumers from deceptive and manipulative tactics (Brenncke, 2024; Esposito and Ferreira, 2024).

While our model is anchored in the EU's Better Regulation Agenda, EBPM is not exclusive to Europe. Countries such as the United States, Japan, India, Ghana, and the UK have all developed EBPM initiatives. These include interventions based on administrative data analysis, behavioral insights, and field experiments — from targeted parenting support programs in Nashville[7] (Shapiro et al., 2024), to textbook trials in Kenya (Glewwe et al., 2007), to energy efficiency policies in the UK (Department for Business, Energy, and Industrial Strategy, 2023) or breastfeeding programs in Ghana (Yale School of Public Health, 2017). Such examples show that, although institutional settings vary, the core elements of science-for-policy models are increasingly global.

Coming back to the EU's use of EBPM for consumer protection, the same rationale in consumer protection law of protecting vulnerable individuals can be applied to the field of service robotics as well. Robotics research and manufacturing require significant resources and technological know-how, which naturally puts manufacturers in a much stronger financial and information position than their potential users (Kotrotsios, 2021). The New Legislative Framework facilitates industry to adopt standards that flesh out the ideals and goals of certain pieces of legislation, robot manufacturers have the upper hand in developing standards that help them comply with the given norm (Longo and Yasumoto, 2024). This further increases the power asymmetry between manufacturers and end users of the technology, as the latter have traditionally been excluded from the development of standards (Balzarova and Castka, 2012).

In this respect, it is unsurprising that some of the current safety standards for service robotics overlook gender and sex considerations in robotics design, presenting problems for female populations (Fosch-Villaronga and Drukarch, 2023). Cognitive and emotional aspects are often disregarded when these systems engage in social interaction with users and elicit emotional responses (from the systems or the users) (Häuselmann et al., 2023). Furthermore, the weaker party protection rationale has traditionally emphasized protecting vulnerable groups, including persons with disabilities, minors and older adults (Múgica, 1990), which many robotic solutions target (Tröbinger et al., 2021). Therefore, the EU approach to EBPM in general, and for consumer protection and user safety in particular, is applicable to the robotics sphere. Given the rapid pace in development of robotics technology and its increasingly ubiquitous and pervasive nature in everyday life, this is an urgent issue that needs to be addressed.

Although policymaking and science are separate domains with diverging views on what evidence should guide decision-making, bridging this gap can provide significant value in solving complex societal problems (Sienkiewicz and Mair, 2020). The UK Science Council defines science as *the pursuit and application of knowledge and understanding of the natural and social world following a systematic methodology based on evidence*.[8] The EC, however, explains that *evidence* is "*multiple sources of data, information, and knowledge, including quantitative data*

[4] *See* https://single-market-economy.ec.europa.eu/single-market/european-standards/harmonised-standards_en

[5] *See* https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02012R1025-20230709.

[6] *See* https://knowledge4policy.ec.europa.eu/home_en.

[7] *See* https://www.familycentertn.org/our-programs/.

[8] *See* https://sciencecouncil.org/.

such as statistics and measurements, qualitative data such as opinions, stakeholder input, conclusions of evaluations, as well as scientific and expert advice" (EC, 2021). This broad conceptualization includes scientific evidence as one of the critical elements of the evidence-based approach, which is the scope of this paper.

Evidence can be considered good evidence when it comes from many sources reflecting a diversity of views and when the evidence is robust and devoid of bias or uncertainty (EC, 2021; Gluckman et al., 2021). When evidence is reliable and based on good quality research, it can be the key tool in guiding better regulation, among other things by (EC, 2023a) (1) precisely capturing the problem at hand, (2) identifying why regulatory intervention is necessary and (3) assisting in developing policy initiatives.

Therefore, (i) objectivity of the research and (ii) analysis of different opinions are key pillars for generating cogent scientific knowledge (Gluckman et al., 2021). Although eliminating all kinds of biases from scientific research is easier said than done (Wilholt, 2009), it is still worth pursuing. Ultimately, generating evidence requires various decisions regarding what evidence to produce and how to interpret it, decisions that may inevitably reflect the socio-political value system of the decision makers (Solow-Niederman, 2023). However, if these decisions are grounded in reasonableness and amenable to input from different stakeholders and revisions, the ensuing evidence can be useful.

High-quality evidence alone is not sufficient for policy making (Gluckman et al., 2021). Evidence must be translatable into cogent policy solutions. In other words, 'good evidence' in a policy context is the evidence that (i) can "*address the key policy concerns at hand*," (ii) is "*constructed in ways useful to address the policy concern*," and (iii) is "*applicable to the local context*" (Parkhurst, 2017). This approach has been seconded by the Joint Research Council (JRC), the EC research institution providing independent scientific and technical support to the EU in the fields of health, safety, and environment, climate change and energy, agriculture, food, and bioeconomy, transport, infrastructure, and mobility, and security and defense (Sienkiewicz and Mair, 2020). This is called *knowledge brokering* and refers to the different ways of linking knowledge generation and reuse, which can happen in interactive or more passive settings and at the organizational or individual level and can range from science communication (translating scientific findings in lay people terms) to the co-production of knowledge with different stakeholders (Bielak et al., 2008; Turnhout et al., 2013).

Therefore, to ensure that scientific evidence is conveyed objectively and effectively to policymakers, intermediaries —known as knowledge brokers— are needed to connect the scientific community and policymakers (Gluckman et al., 2021). These knowledge brokers cannot come from isolated disciplines within science because they cannot properly inform the public and policymakers, as otherwise they may neglect the inclusionary social aspect of these recommendations provided by the social sciences (Turnhout et al., 2013). Because knowledge brokerage presents the synthesis of evidence to policymakers in a palatable way, those using this method should not forget their reflexivity as their values are embedded in the process (Etherington, 2004). Reflexivity, borrowed from anthropology, consists of an internal dialogue and self-evaluation on a continual process of the researcher's position in society, acknowledging that this position might affect the process and later on results. Reflexivity asks the researchers to turn their lens back onto themselves, challenging the knowledge production as objective (Berger, 2015). The knowledge broker presents the core values of trust, transparency and legitimacy, knows the vast knowledge systems and epistemologies and considers their own values and morals (Gluckman et al., 2021).

Knowledge brokers are connected to academia and policymaking and offer an impartial opinion, knowing they can be labeled as connected to one side more than the other. They need to be transparent, even when presented in brief reports or more broadly through the media. Knowledge brokers can provide robust, organized critiques based on peer reviews. Nevertheless, they should not forget that local knowledge has a unique perspective that can add something to the body of knowledge and the researcher's own values and biases (Gluckman et al., 2021). However, interacting with policymaking involves knowing that the process is not linear (Pielke Jr, 2007). It heavily depends on complex interactions between communities, interest groups, citizens and experts and on timing because actual political change happens when there is interest in the problem and "...a politically acceptable and scalable solution" is presented at that exact moment (Gluckman et al., 2021).

3. Methodology and design mechanisms

The generation of the Science for Robot Policy model proposed in this paper constitutes a genuine piece of constructive research. As Lehtiranta et al. (2015) indicated, the primary purpose of constructive research is to provide solutions to practical problems while producing an academically theoretical contribution. Thus, the model has the goal of addressing a specific research problem by creating a structured way to solve, understand, explain, or model it. This approach is commonly used to define and solve problems, as well as to improve an existing system (Oyegoke, 2011).

The philosophy underpinning the constructive research paradigm as a method is the construction of artifacts, practical or theoretical, such as models, systems designs or algorithms, based on existing knowledge but used in novel ways (Crnkovic, G.D., 2010). Indeed, it is the addition of missing links between well-grounded pieces of knowledge that differentiate constructive solutions from other systematic methodologies such as grounded theory. As Crnkovic (2010) indicates, constructivism-based solutions are designed and developed, rather than discovered. In this sense, a constructive research approach is a problem-solving method that, although it relies on different tools, aims at producing novel solutions to both practical and theoretical questions.

Its application within legislative and policymaking processes has been limited to date. This paper copes with the regulatory disconnection through a working regulatory model capable of addressing the regulatory gap created by the pace of technological innovation within the robotics realm.

The CRM is adjusted to the following structure: (1) the detection of a practically relevant problem, as we will explain in our case, the regulatory disconnection caused by the different velocities of technology development on the one side, and the regulatory process, on the other; (2) the revision of literature to get a comprehensive undertaking of the reality is intended to deal with; (3) the design of a new construct, in our case the 'Science for Robot Policy' model; (4) the validation and demonstration of the workability of the new construct; (5) the study of the theoretical connections and the research contribution of the solution concept; and (6) the examination of the applicability of the proposed solution. In this sense, the following sections are structured according to the aforementioned research process that is traditionally followed in a constructive research approach (Oyegoke and Kiiras, 2009), outlined in the Fig. 1.

Oyegoke (2011) highlights that the process is not strictly linear but dynamic and interactive across different phases. Consequently, the final model presented in this paper, *Science for Robot Policy*, represents the latest iteration of a multi-stage process. Here, the phases guide the reader through the elaboration process rather than a precise report of the actual workflow followed. Thus, to enhance clarity and facilitate understanding, this paper adopts a systematic structure in its presentation.

In this sense, Section 4 exposes the practically relevant problem that the model intends to address and provides a general comprehensive understanding of the topic (Phase 1 and 2). Section 5 presents the design of an applicable regulatory process that may overcome the research problem addressed (Phase 3). Section 6 shows the validation of the model (Phase 4). Section 7 outlines the theoretical connections and the research contribution of the solution concept (Phase 5). Section 8 examines the applicability of the solution (Phase 6).

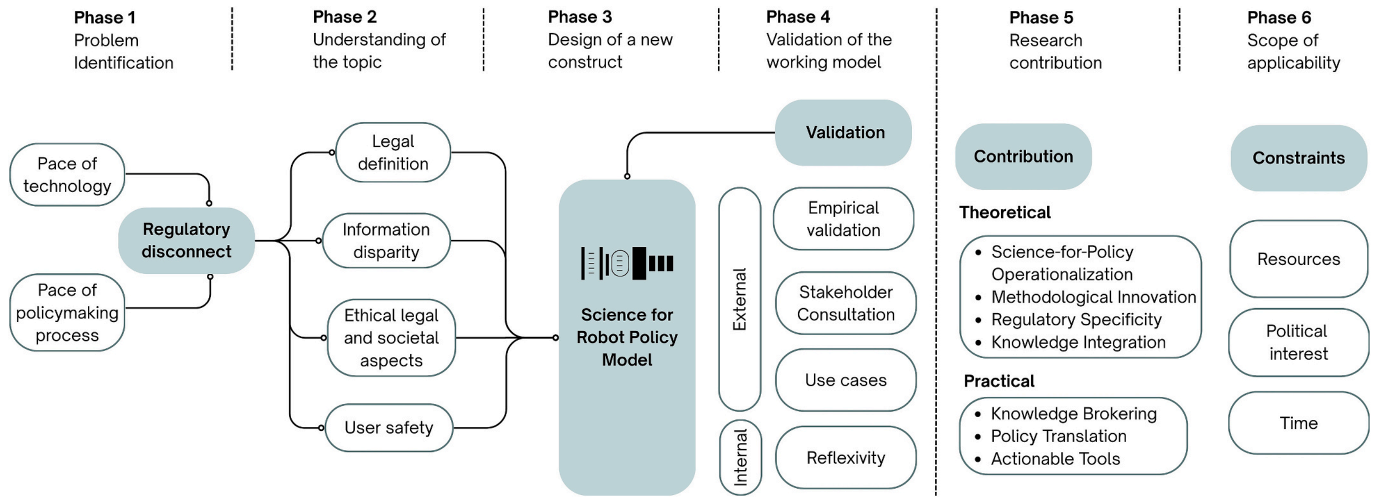

Fig. 1. This figure illustrates the constructive research approach to addressing regulatory disconnect in service robotics.

4. Theoretical problem identification and understanding of the topic: Service robot regulatory disconnect

In the field of service robotics, the growing gap between the policy cycle and technological change results in a regulatory disconnect, when either 'the covering descriptions employed by the regulation no longer correspond to the technology' or 'the technology, and its applications raise doubts as to the value compact that underlies the regulatory scheme' (Brownsword, 2008; Brownsword and Goodwin, 2012). This regulatory disconnect may, in turn, result in robot developers not integrating essential considerations into their designs to make robots safe and sound for a variety of users (Calleja et al., 2022). There are five reasons for this regulatory disconnect:

First, there is no single legal definition accepted by all for what constitutes a service robot, distinguishing this type from robots used in industrial applications (Fosch-Villaronga and Drukarch, 2021). The ISO defines *service robots* as 'robot in personal use or professional use that performs useful tasks for humans or equipment' (ISO 8373:2021, Section 2.10). These robots are usually found near humans in uncontrolled environments. While several sectors benefit from these robots, the existing legal framework may not adequately address safety-related issues. Service robots do not conform to merely physical human-robot interaction (pHRI) and can also have a social aspect (Fosch-Villaronga, 2019). Current frameworks tend to focus mostly on physical safety, neglecting other essential aspects such as security, privacy, psychological aspects and diversity, which play a crucial role in robot safety (Martinetti et al., 2021; Fosch-Villaronga and Poulsen, 2022).

Second, unfortunately, our understanding of these robots, their implications and their regulation, is not keeping pace with the rapid acceleration of technology (Collingridge, 1980). The pacing problem (Marchant, 2011), which means that regulatory and ethical frameworks are unable to keep up with technology that is racing faster than ever before, indecision in striking a balance between innovation and the protection of fundamental rights, and the uncertainty as to whether current regulation is adequate or whether we need to draft new regulations for robots, poses dilemmas regarding robotics regulation (Leenes et al., 2017; EurParl, 2017; 2019) which have yet to be resolved by leading public policymakers. In fact, current standards and laws have so far failed to adequately frame robotic technology, even though it is a remarkably sensitive domain (Calo et al., 2016; Fosch-Villaronga, 2019; Winfield, 2019; Salvini et al., 2021).

One instrument that has failed to respond to these technological advancements is ISO 13482:2014, an international standard that establishes safety requirements for personal care robots (Fosch-Villaronga, 2019). This standard is a harmonised C-type standard under the Machinery Directive 2006, meaning that there is a presumption of conformity with the Machinery Directive if a robot meets the requirements of this standard (Directive 2006/42/EC, Article 7(2)). Putting aside for a moment the various criticisms of such standards from a legal and policy perspective (Guihot et al., 2017; Fosch-Villaronga and Golia Jr., 2019), it is relevant to note that ISO 13482:2014 established a new category of robots – personal care robots – that are not medical devices or industrial robots. They are service robots that perform actions that directly contribute to improving the people's quality of life, excluding medical applications (ISO 13482:2014, Section 3.13). However, the standard did not define *personal care* or *quality of life*, which tend to be indicators of the medical (device) field. The standard also included several confusing categories of robots, making it difficult to determine whether a particular robot falls under this standard at all (e.g., if a robot is used for rehabilitation, then is it a medical device and hence excluded from this standard) (Fosch-Villaronga, 2016). The growth of robotic technology since the inception of this standard has resulted in further ambiguities and issues, such as the fact that the standard does not adequately address non-physical safety issues posed by socially assistive robots (Fosch-Villaronga, 2019; Martinetti et al., 2021). This has led ISO to revise this standard and eliminate such a category under ISO/DIS 13482:2024.

Third, information disparity also seems to be an important cause of such disconnection (Breyer, 1993). In theory, the Regulation 1025/2012 on European Standardization aims to combat such asymmetries in Art. 5.1 by mandating that "European standardisation organisations shall encourage and facilitate an appropriate representation and effective participation of all relevant stakeholders, including SMEs, consumer organisations and environmental and social stakeholders in their standardisation activities." However, research shows that, in the context of service robotics, standard makers have not had direct engagement with end-users, consumer groups, or vulnerable stakeholders, leading to critical gaps in how standards impact real-world users (Fosch-Villaronga et al., 2020; Fosch-Villaronga and Drukarch, 2023).

Fourth, service robots also raise ethical, legal, and societal challenges that scholars have identified over the past decade (van Wynsberghe, 2016; Riek, 2017; Custers et al., 2017; Fosch-Villaronga, 2019). Robot developers often fail to integrate essential considerations into their designs and may develop systems that can harm society, for example by failing to consider culture-specific designs (Lim et al., 2021; Mansouri and Taylor, 2024). Missing this in turn deepens the regulatory disconnect. Research continues to show how physical assistants/wearable robots (Bessler et al., 2021) and social robots (Fosch-Villaronga, 2019) can harm users in different ways. For instance, as the number of robot-assisted rehabilitations increases, robot failures and adverse events in these contexts also increase (Liu et al., 2023).

Fifth, the use of scientific knowledge also needs to guide robotics regulation as there are inherent concerns about user safety. However, knowledge about these harms and adverse events is scarce, and science has done little or nothing to synthesize this knowledge, incorporate these lessons learned, and engage with policymakers so that together they can understand what safeguards policy should include to ensure the next generation of robots is safe and sound (Fosch-Villaronga and Golia Jr., 2019).

In essence, the exposition of such a disconnection underscores the problem's practical relevance and justifies using a constructive research approach to develop a targeted, evidence-based regulatory model for service robotics.

5. Designing a new construct: Science for Robot policy

The evidence-based policy movement was developed during the 1970s and enjoyed a renewed strength in the late 1990s (Head, 2016). It promotes in-depth analysis of policy and program options, providing valuable insights to assist policymakers in their ongoing efforts to shape and improve policies and programs. In this sense, evidence based-policy refers to the method of policy development that consults facts and credible, relevant evidence to make decisions, over political opinion or theory.

In this state of affairs, we propose our model for *science for robot policy*. Science for robot policy involves gathering, generating, analyzing, and interpreting information from scientific research, stakeholder engagement, and iterative testing to understand complex issues surrounding robot development and their interaction with humans and the environment to provide the foundation for informed decision-making that anticipates and keeps pace with robotics' rapid evolution.

(Fig. 2) As depicted in Fig. 1, this approach is collaborative and interdisciplinary and begins with early identification and prioritization of risks associated with robotic applications. By drawing on multiple data sources—such as literature reviews, industry insights, and input from diverse stakeholders such as policymakers or affected users—Science for Robot Policy aims to assess potential challenges before they scale comprehensively. Experimentation is then used as a dynamic tool to test solutions and generate policy-relevant data. Starting in controlled simulations at the early stages of development, the testing can progressively advance to more realistic environments like testing zones, living labs, and actual market settings. This "test-and-evolve" rather than 'solve-and-leave' approach can help address novel problems while providing valuable feedback to refine technologies and policies continuously.

The next step is to transform the raw data generated from the tests into structured, policy-relevant information, which may be challenging. However, transparent and objective scientists can attempt to accurately represent data and present it to policymakers to support well-informed and timely decisions, even in the face of complex, unknown risks. Since information is only sufficient if transformed into actionable knowledge that informs outcome-based policies, we designed our model to be adaptive, helping regulators develop guidelines that can evolve with the technology. These guidelines can take various shapes and forms, like benchmarks, standards, and laws that build on each other. This progressive juridification of the findings provides reassurance about the model's adaptability, which can be readapted in more flexible frameworks (i.e., standards) than others (i.e., laws). This approach can ensure that policies remain relevant, resilient, and reflective of societal needs and values as robotic technologies advance.

In the following subsections, we explain the model of science for policy in detail from its departure point (step 1), to the generation of data via risk identification and prioritization (step 2) and experimentation (step 3) and how we propose to transform data into information (step 4), and, finally, how this information can be transformed into actionable knowledge (step 5).

5.1. Step 1: Framework identification - the law or the Robot?

Our legal system operates on the principle of *horror lacunae*, an aversion to gaps in the law. From the moment we are born, even before, until long after we have passed away, our lives are subject to a complex web of regulations. Legal entities, nature, practices, and *things*, as we call them in law, are not exempt from this regulatory oversight. Under this premise, past EU projects, such as RoboLaw, Inbots, or RockEU, have typically used top-down approaches to conduct general ethical, legal,

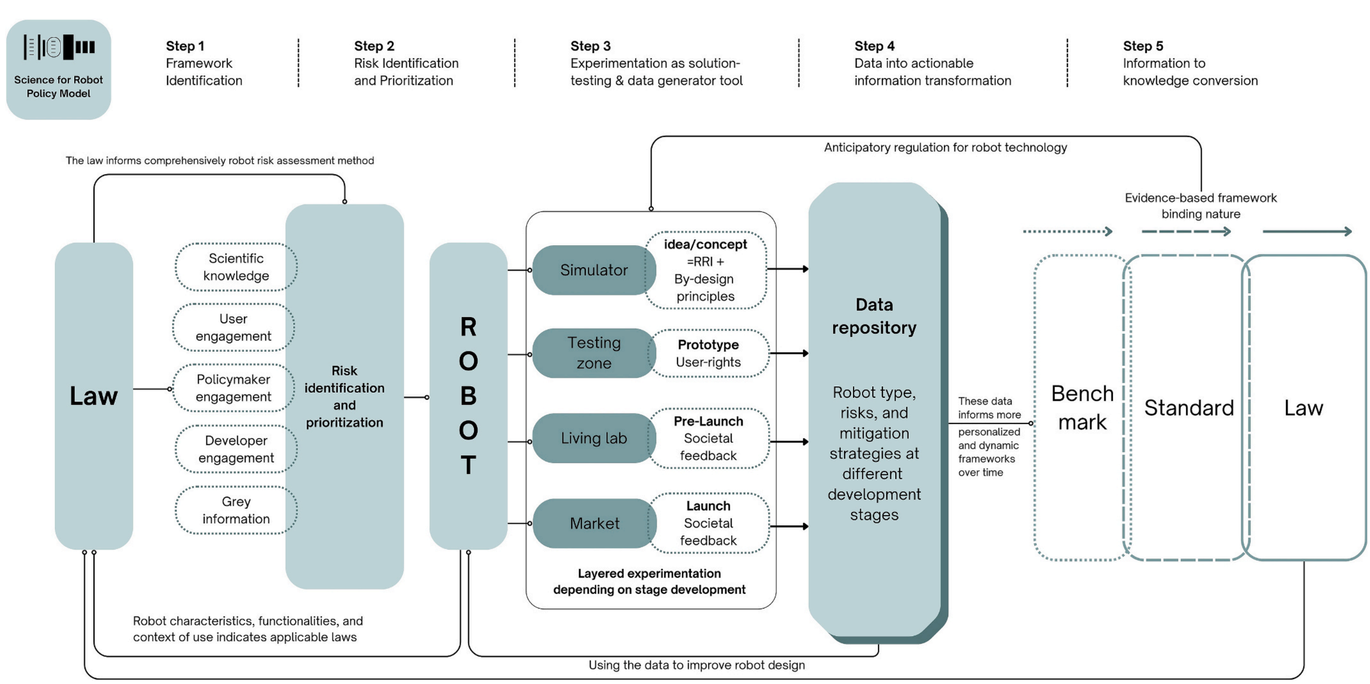

Fig. 2. Science for robot policy: an evidence-based policy cycle model for robot technology using different knowledge sources to identify and prioritize robot regulatory risks, test solutions in experimental zones, and generate policy-relevant knowledge and leverage it to impact law, practices, and user rights dynamically.

and societal (ELS) assessments of robotics based on existing laws (Leroux et al., 2012). For instance, privacy issues in assistive robotics have been addressed under general data privacy laws (Günther et al., 2012). From rehabilitation to surgery, farming, and logistics, robots navigate legal categories such as medical devices, products, toys, and machinery, each of which is governed by existing laws (Holder et al., 2016; Nevejans, 2017; Turner, 2018). These existing regulatory frameworks (some of which are under revision) provide the initial structure and scope where robotic technologies must operate, setting boundaries on several aspects, including safety, privacy, and liability (Leenes et al., 2017; Fosch-Villaronga and Heldeweg, 2018). Given that the applicable legal framework is determined based on the robot's characteristics and use context, the departure point of science for robot policy is the law, because the law does not regulate "robots" as a distinct legal category but through existing legal classifications like machinery, medical devices, toys, etc. In other words, it is the nature of the robot — what it is and how it is used — that determines which legal framework governs it (Fosch-Villaronga, 2019).

However, robots do not fit neatly into any single area of law—they may be governed by health law, labor law, data protection law, consumer protection law, and perhaps newly enacted legislation covering AI. Also, laws may have been enacted when some of these technologies were not invented yet, so unsurprisingly, they may also blur traditional legal categories, making it unclear which legal frameworks apply to specific, new cases. For instance, a mosaic of different regulations may apply to robots using cloud services such as speech recognition or navigation, including the General Product Safety Regulation, the Product Liability Directive, the Machinery Regulation, or the General Data Protection Regulation 2016/679 (Fosch-Villaronga et al., 2018; Fosch-Villaronga and Millard, 2019). This patchwork can complicate efforts to assess and regulate their use effectively.

Therefore, for the purposes of science for robot policy, the law is seen as a framework that is the starting point; not as a prescriptive or authoritative guide but as a reference point, offering a structured basis for discussion while leaving room to critically examine its assumptions, limitations, and adaptability to evolving social and technological contexts. The law is not only the starting point of our model but also its final step. Essentially, the model's outcomes aim, among other things, to improve existing regulations, creating a flow that makes this approach dynamic rather than static (Fosch-Villaronga and Heldeweg, 2020). That said, the first step in our model consists of identifying the regulatory framework that governs human-robot interaction, which regulation is intended to be improved.

5.2. Step 2: Risk identification and prioritization

The second step in our model is risk identification and prioritization. Identifying regulatory gaps in robotics requires addressing *known unknowns*—areas we know need clarification—and the more elusive *unknown unknowns*, representing issues we have not yet anticipated or understood (Pawson et al., 2011); in other words, gaps and dissonances. While *known unknowns* (like user privacy risks in assistive robots) are critical and can be addressed via existing frameworks, *unknown unknowns* are potentially more impactful because they expose unforeseen challenges that can lead to regulatory blind spots.

In robotics, *unknown unknowns* can emerge from human-robot interaction factors we have not yet linked to the law, such as the extent to which robots' embodiment affects user safety, the role emotions play in supporting robot operations, how progressive autonomy levels affect responsibility and oversight, or how intersectionality impacts user safety (Drukarch and Fosch-Villaronga, 2022; Häuselmann et al., 2023; Fosch-Villaronga et al., 2023a, 2023b; Paterson, 2024). If left undiscovered, misunderstood, or understood too late, these uncharted areas may introduce risks that would otherwise only become apparent after issues arise, often when harm has already been done to users and society at large. Hence, it is essential to turn those *unknowns* into *knowns* (Pawson et al., 2011).

Knowledge about robots' regulatory gaps and dissonances may come from different sources. Our approach to capturing and uncovering these *unknown unknowns* combines (1) scientific knowledge, (2) broad stakeholder engagement to whom robot technologies raise particular legal issues, including users, developers, and policymakers, real-world experimentation, and (3) gray information:

1. Scientific Knowledge: Systematic literature reviews executed in a rigorous and methodological manner can lay the foundation for academic research and contribute to creation of practical and policy guidelines (Snyder, 2019). Especially when it comes to normative literature concerning ethical aspects, systematic reviews can enable better informed decisions and can further the research that underpins these decisions, in fields including robotics (Vandemeulebroucke et al., 2018). Thus, the scientific knowledge generated through reviews can provide rigorous, evidence-based insights into robotics' ELS impacts, including unknown risks, legal debates, and evolving legal interpretations. By synthesizing this information, we can establish a solid foundational understanding of what issues are known, which are unknown, and where regulatory frameworks are either emerging, failing, or lacking. In this sense, for instance, a systematic review aimed at addressing definitional ambiguities in social robotics, as well as gaps in regulatory and academic consensus, can contribute to the development of robust, evidence-based policies. Identifying the characteristics, functionalities, and contexts of use for social robots can facilitate the application of relevant legal frameworks. This process can also help bridge the gap between academic definitions of social robots and the ISO standard definition of a Mobile Service Robot, leading to more comprehensive and standardized taxonomy (Schwed-Shenker et al., 2025). In the same vein, a systematic review on 'Physical Assistant Robots', can provide conceptual clarity on what these robots are, the applicable legal framework, and how to address user safety risks associated with these robots (Shaffique and Fosch-Villaronga, 2025).
2. Stakeholder Engagement: Engaging stakeholders—such as users, developers, and policymakers—brings real-world perspectives into the conversation. For instance, in discussing what issues a blind person faces daily, they might say that they hit their head often since the only point of contact they have is a stick on the floor (Manduchi and Kurniawan, 2011). As we will explain in 6.1, developers provide practical insights into how existing regulations impact their robot development, highlighting areas where regulations may be ambiguous, outdated, or overly restrictive (Drukarch et al., 2023). Policymakers, in turn, can clarify what aspects are covered and which challenges exist in creating fair and enforceable rules that serve all segments of society (Fosch-Villaronga and Heldeweg, 2018). This direct multi-stakeholder engagement is crucial to identifying and prioritizing regulatory gaps that may not yet be addressed individually.
3. Gray Information: G*ray* information, e.g., information found in blogs, reports, policy briefs, and opinions (from the European Data Protection Board or euRobotics), or other sources is crucial in uncovering regulatory blind spots and inconsistencies between policy goals and real-world practices (Godin et al., 2015). For instance, Sanz-Urquijo et al. (2023) illustrate how EU-funded AI research projects for law enforcement often fail to align with the EU's trustworthiness principles. Disparities in project language, funding allocations, and stakeholder composition highlight gaps that formal evaluations might overlook. Such overlooked details—embedded in project structures, funding priorities, and dissemination strategies—can provide policy-relevant insights, revealing where regulatory frameworks lag behind technological development and where informal norms emerge without clear guidelines. In the field of robotics, Søraa and Fosch-Villaronga (2020) noted, from an analysis of gray information, including from Google search engines and

manufacturers' websites, that exoskeleton design does not always account for the physical differences between male and female users, including physiological characteristics such as height, weight and body dimensions.

This comprehensive approach will facilitate the discovery of overlooked risks, enable us to map where existing frameworks fall short, and identify which principles could apply to the novel challenges that robots introduce. It also helps avoid redundancies or conflicts with established laws and highlights areas where new, tailored regulations might be required.

5.3. Step 3: Experimentation as a solution-testing and novel data-generator

The third step involves progressing from identifying and prioritizing potential regulatory issues to empirically testing and contextualizing these issues in different environments. Depending on the technology readiness, such experimentation may vary. At the early stages of development, experimentation may be more explorative and aimed at uncovering unknown risks and setting foundational standards. As technology advances, experiments become more targeted, testing specific hypotheses and regulatory solutions (Hart, 2012). We propose to look into four primary experimental environments—simulators, testing zones, living labs, and markets—to offer structured stages for generating relevant data and refining policies.

1. Simulators may be helpful at the idea/concept stage, as the flexibility and the easiness of the environment can be an effective tool to illustrate the robot, its behavior, and its parts. Simulators are designed to provide controlled, risk-free environments that allow developers to explore basic interactions, mundane tasks, or potential hazardous situations for humans with robotic technology (Huck et al., 2021). These scenarios may help identify potential safety, privacy, or usability concerns before manifesting in real settings, or help analyze the impact of current law or a reform proposal – as happened with Luxembourg's Income Tax Law in 2016 (Soltana, 2015). Although there might be a translation problem between legal principles and computational simulation, the flexibility and integrative nature of simulators may pave the way for the integration of 'by design' considerations into the system, such as privacy considerations (under Art. 25 of the General Data Protection Regulation) (Fosch-Villaronga, 2019; Albuquerque Wheler de et al., 2021).
2. Testing zones. As robots become more refined and have a physical embodiment, testing zones allow for controlled but more realistic experimentation. Though few, these zones started to emerge in different locations worldwide. *Tokku* zones in Japan have been used for humanoid robots (Weng et al., 2015); in Pittsburgh, the Human Engineering Research Laboratories (HERL) created a testing laboratory for ISO and the American ANSI/RESNA) Standard tests for powered wheelchairs and lower-limb prosthetic devices; and several *automotive proving grounds* have been created worldwide for self-driving car testing.[9] These zones aim to replicate specific, real-world environments where the technology can be assessed for compliance with specific safety standards in semi-real conditions. For instance, the University of Leon recently got awarded the European Robotics League Consumer Service Robots Test Bed Certification for their *Leon@Home Testbed.*[10] This testing zone aims to benchmark service robots in a realistic home environment. Testing zones allow observing specific robot behaviors in specific scenarios in a reproducible manner with specific target subjects. Isolating certain aspects can be instrumental in identifying certain causal relationships between attributes that might otherwise be confounded. The role of knowledge brokers in testing zones is twofold. On the one hand, they should define the objectives to be studied (for instance, based on step 1 and 2, develop the correlation between protective/emergency stops and stability), set the controlled scenarios (e.g., ascending/descending stairs with exoskeleton), develop protocols that can be replicable (e.g., questionnaire for user exoskeleton interaction observation), and determine the performance indicators (e.g., stress, foot placement estimates, perceptibility) (Calleja et al., 2022). On the other hand, they should synthesize the data into information (*see* Step 4).
3. Living labs. As robots move into the market, the level of control decreases at the expense of greater representation of reality. Living labs are "open innovation ecosystems in real-life environments based on a systematic user co-creation approach that integrates research and innovation activities in communities, placing citizens at the center of innovation."[11] They differ from testing zones: while testing zones focus on controlled, specialized environments designed to simulate specific real-world conditions, living labs place technologies in authentic community settings to observe human interactions within the complexities of daily life (Søraa et al., 2021). Individual, social, and psychological factors may become more visible at this stage, and unexpected issues may emerge, such as users' comfort, trust, or unintended impacts on privacy. It may also be that users do not want to use the robots in the end, due to disenchantment, the end of the novelty effect, lack of motivation, as well as restrictions and problems (de Graaf et al., 2017). But it can be that more mundane, practical issues arising with daily, more frequent use of the technology are discovered. For instance, while the Pepper robot usually works well in controlled environments, it struggles to perform well after some time in crowds because the robot fan is located next to its microphones, which hinders effective speech recognition. In combination, these insights are essential for policies that must account for robot safety requirements but also societal acceptance and safeguard diverse user rights, especially when robots operate directly with people.
4. Markets. Finally, once robots are fully deployed in the market, observation of their operation tests regulatory and technology readiness, as real-world exposure reveals long-term issues, like maintenance challenges, ethical dilemmas, and unforeseen user behaviors and could therefore provide some useful insights that could inform policies and regulations if captured. There is not a dedicated market surveillance entity for robots, and there are several mechanisms that could monitor their performance. The EU's Safety Gate system,[12] while primarily focused on non-food products, can serve as a product safety model for a rapid alert system for dangerous robotic products, which would allow the sharing of information about hazardous robots in a duly manner where authorities can take swift action to protect consumers. To that end, manufacturers should implement robust programs to monitor product performance, identify potential issues, and, ideally, report them in a centralized incident reporting system. These feedback loops with manufacturers, which would gather real-world data, could help authorities, over time, identify trends and patterns in accidents and malfunctions, which could ultimately support the update of safety protocols or mandatory user training, leading to the development of more effective safety standards and guidelines (Malm et al., 2010; Fosch-Villaronga and Golia Jr., 2019).

The reality may be that while incidents in controlled environments

[9] *See* a world map of proving grounds at https://dewesoft.com/blog/list-of-automotive-proving-grounds.

[10] *See* https://eu-robotics.net/wp-content/uploads/ERL-CSR_TestBedCertification_ULeon_web.pdf.

[11] This definition has been extracted from The European Network of Living Labs (ENoLL). Link: About Us - ENoLL

[12] *See* https://ec.europa.eu/safety-gate/#/screen/home.

may provide great incentives to improve systems, incident reporting in robots already in the market can be affected by reluctance to disclose problems due to reputational concerns or fear of liability (Calleja et al., 2022). Companies may not want to appear negligent, fearing legal repercussions or compromising their market position and investor confidence. Not having mandatory reporting mechanisms and related protections for disclosure may create a bias towards underreporting, i.e., incidents that could offer valuable lessons remain unshared, hindering regulatory learning possibilities (Alemzadeh et al., 2016).

5.4. From data to policy-relevant knowledge

Science for robot policy aims to leverage data captured via scientific insights and stakeholder engagement as well as generated in simulators, testing zones, living labs, and markets to reduce information imbalances between different stakeholders and eventually support evidence-based policy change in service robotics. While many science-for-policy frameworks treat the transformation of data into regulatory knowledge as a single step, we deliberately distinguish between two distinct stages in this model. Step 4 concerns the technical and analytical processes by which raw data is validated, structured, and contextualized into usable information (Zins, 2007). Step 5 then addresses how that information is adapted, framed, and communicated as actionable knowledge for various regulatory audiences, particularly through the interpretive work of knowledge brokers. This separation allows us to highlight the unique communicative and epistemic challenges involved in science translation for policy use.

5.4.1. Step 4: Transform data into policy-relevant information

Structuring and processing data generated from the testing zones is crucial to identify which data is policy-relevant. This process involves transforming low-meaning, low-value data into valuable expertise that can be applied to legal contexts and robotic design. The primary data-generation process aligns with the principles of anticipatory regulation, relying on experimentation across various testing zones, living laboratories, simulators, and market observations.

In our model, data refers to raw, unprocessed observations collected through experimentation, stakeholder input, or scientific insights. For instance, a testing environment might record the frequency of malfunctions in a robotic system. To transform data into information, the data is cleaned, categorized, and analyzed to identify trends, patterns, and correlations. For example, “30% of robotic malfunctions occur during navigation in confined spaces.” However, raw data—symbolic representations of observable properties derived from observation and experimentation—must be contextualized and transformed into usable information through relational connections. This data-to-information process involves converting raw data into organized, relevant, and insightful information. Typically, this process includes data collection, extraction, cleaning, analysis, and visualization. Techniques such as statistical analysis, visualization, and data modeling can be used to identify valuable patterns, trends, and correlations in data gathered from experimentation and observation, ultimately providing actionable insights. Information is frequently understood as data that adds value to the understanding of a subject (Chaffey and Wood, 2005).

This step focuses on the structuring and contextualization of raw data so that it becomes meaningful and comparative across domains. For example, sensor logs from exoskeleton trials become policy-relevant information once they are categorized by failure type, environment, and user profile, and compared to thresholds defined by risk metrics (Calleja et al., 2022). This information remains domain-specific —understandable to technical experts or regulators— but is still not yet actionable knowledge. Its transformation into knowledge depends on the ability to frame this information for distinct regulatory needs, which is the aim of Step 5.

To support this transformation of information into regulatory knowledge, we also recognize that evidence is never neutral. Reflexivity — the critical awareness of how knowledge is produced and interpreted — is vital. This issue is explored in more detail in Section 7, where we discuss how situated knowledge strengthens the ethical and epistemic integrity of the model.

5.4.2. Step 5: Information to knowledge for policymakers

Step 5 is about transforming information generated from raw data in Step 4 to knowledge for policymakers. Information becomes knowledge when interpreted, validated, and contextualized in a way that makes it actionable. This requires linking analyzed data to broader objectives, such as regulatory compliance, user safety, or societal impact. Continuing the example, knowledge would address the “why” behind the pattern—e.g., “malfunctions in confined spaces occur due to inadequate sensor calibration, which raises risks for user safety.” This knowledge allows stakeholders to understand the implications of the information and determine the necessary actions, such as revising safety standards or encouraging new sensor technologies.

In Step 5, structured information becomes policy-relevant knowledge — not by further technical analysis alone, but through translation, framing, and adaptation. This involves tailoring information to be understandable, timely, and directly applicable to decision-makers, developers, and end-users. For instance, policymakers need synthesized insights on whether a technology violates existing safety thresholds or if a standard needs updating. Developers may require clear benchmarks or decision trees. Users may need simplified summaries to assess personal risk.

Here, knowledge brokers are central. They act as intermediaries who understand both scientific content and policy processes. Their role is to repackage technical findings into accessible formats — such as briefings, legislative memos, or standard-setting inputs — and ensure alignment with regulatory agendas (Gluckman et al., 2021). Brokers also help prioritize and contextualize findings, making decisions more grounded, inclusive, and forward-looking (Etherington, 2004). Without this interpretive layer, even well-structured information risks being misunderstood, ignored, or misapplied (Turnhout et al., 2013).

This evidence-based mechanism may eventually guide policy development for robot technologies through learning processes. These may follow an instrumental approach, where knowledge directly informs decisions, or a conceptual approach, where new ideas and perspectives gradually influence policymakers and permeate the policy system (Stewart, 1981; Hertin et al., 2009). Interventions may occur in different ways, including ex officio (initiated by authorities to foster legal clarity and regulatory incentives) or *ad petitionem* (in response to requests from developers or stakeholders for legislative actions promoting innovation) (Fosch-Villaronga and Heldeweg, 2018).

In summary, the proposed model operationalizes constructive research principles by offering a pragmatic and adaptive solution that connects empirical insight with regulatory design, directly addressing the policy lag in service robotics.

6. Demonstrating that the new construct works: Stakeholder engagement and empirical validation

As indicated, the proposed working model is a theoretical construct designed for implementation in the policymaking process. The validation of this model can be looked at from *ex-ante* and *ex-post* lenses. From an *ex-ante* perspective past experiences help forecast the model’s efficiency and applicability. In this sense, previous research may help us to anticipate the validity of *Science for Robot Policy*. To this end, we will focus on two European research projects that, in a certain way, share key components with the proposed model: LIAISON and PROPELLING. Although separate, both initiatives aim to improve robotic regulations through an evidence-based approach. Moreover, they employ methodological techniques such as stakeholder analysis and experimentation, which are also included in our model.

6.1. Validation of the stakeholder engagement in the construct

The H2020 COVR project[13] aimed to provide a clear, comprehensive, and user-friendly safety assessment process across different robot applications as well as best-practice testing protocols and services through robot development. To that end, a toolkit was created where robot developers can easily access information that would otherwise be difficult to find, for instance, by grouping directive and standards relevant to different types of robots, compiling protocols that are step-by-step guides to validate safety of their systems, and also having a risk assessment tool that compiles typical hazards for those systems (Fig. 3).[14]

However, a mere website that displays information does not ensure that manufacturers understand how to apply those standards, preventing them from expressing compliance-related struggles or gaps and dissonances following standard application (Drukarch et al., 2023). Moreover, such an approach assumes standards are correct while it does not need to be necessarily the case.

The main research question investigated in the LIAISON project was whether compliance tools could serve not just as guidance mechanisms for developers, but also as data sources for iterative regulatory refinement. Robot developers are among the first to identify legal inconsistencies, often encountering unclear categories, contradictory standards, and missing legal definitions during compliance procedures for market entrance (Fenwick et al., 2016; Fosch-Villaronga and Heldeweg, 2018). However, despite their practical experience with regulatory ambiguity, developers rarely contribute directly to the policymaking process–they just ensure their robots comply with existing frameworks. This is done through informative websites like the one created by the H2020 COVR project which helps developers navigate the complex robot regulatory landscape.[15] LIAISON formalized this engagement by introducing a structured developer-regulator feedback loop in which robot developers using the 'compliance tool' developed by the COVR site could, at the same time, provide their insights on gaps and dissonances within those norms (Drukarch et al., 2023). The goal was to operationalize a key principle of the Science for Robot Policy model: that effective governance must be iterative, evidence-based, and participatory.

To test this approach, LIAISON employed multiple research methodologies, including literature review, surveys, workshops, and direct consultations with policymakers and standardization bodies. The project focused on three robotic domains—personal care robots (ISO 13482:2014), rehabilitation robots (IEC 80601–2–78–2019), and agricultural robots (ISO 18497:2018)—each presenting unique compliance challenges that traditional regulatory approaches had failed to address adequately. Rather than relying on static policy assessments, LIAISON treated real-world compliance issues encountered by developers as empirical data points (Drukarch et al., 2022). Surveys and interviews with robot developers revealed that many struggled with unclear regulatory classifications, particularly in cases in which robots blurred traditional boundaries—such as assistive robots that function both as personal care devices and medical instruments. Developers expressed difficulty in determining which legal frameworks applied to their designs, illustrating the regulatory disconnection that the constructive model aimed to resolve (Drukarch et al., 2023).

By systematically documenting the struggles of developers, inconsistencies in legal language, and gaps in existing safety standards, LIAISON demonstrated that interactive regulatory mechanisms—not just top-down rulemaking—could help inform policy frameworks with valuable information about what works and what does not in robot safety compliance. In other words, through iterative engagement, LIAISON validated a core assumption of the Science for Robot Policy model: that engaging with different stakeholders could actively generate policy insights for robot regulation.

The LIAISON experiment yielded critical insights that reinforce the methodological approach of the Science for Robot Policy model:

1. Engaging developers can generate policy-relevant knowledge. By incorporating developer insights into regulatory discussions, LIAISON proved that those working at the forefront of robotics innovation can contribute valuable information about regulatory gaps, mismatched standards, and emerging legal challenges. This supports the Science for Robot Policy model's emphasis on participatory governance.
2. Regulatory ecosystems could benefit from centralized policy-relevant data repository platforms. The study revealed that public policymakers, standardization bodies, and robot developers operate in isolated silos, resulting in misaligned expectations and inconsistent compliance requirements. The LIAISON approach suggests that a centralized mechanism for structured regulatory engagement—-where stakeholders can exchange knowledge—could enhance both legal certainty and technological adaptability.
3. The need for a continuous, evidence-based policy cycle. Robotics regulation must evolve in parallel with technological advancements. LIAISON provided empirical support for the notion that policy iteration should not be reactive (only updating laws in response to crises) but proactive, incorporating ongoing data from compliance experiences into regulatory processes.

LIAISON embodied the principle that constructive research distinguishes itself by not merely analyzing existing systems but constructing new ones, offering novel solutions that integrate existing knowledge in innovative and functional ways (Crnkovic, 2010) by demonstrating that regulatory tools can function as compliance aids and policy intelligence systems—a perspective that was previously underexplored in robot governance (Drukarch et al., 2023). By testing the feasibility of a structured, iterative regulatory model, LIAISON advanced the constructive research paradigm within science for robot policy, providing theoretical contributions—by reinforcing CRM as a valid approach for policymaking research—and practical advancements by validating the utility of developer-policy engagement as a mechanism for regulatory refinement.

6.2. Empirical validation of the construct

While LIAISON validated the Science for Robot Policy model through stakeholder engagement, the PROPELLING project took a complementary, empirical approach. PROPELLING[16] focused on robot testbeds as sources of policy-relevant data, demonstrating how evidence-based regulatory refinement can address the disconnect between robotic innovation and legal adaptation (Calleja et al., 2022).

PROPELLING aimed to explore how robot testing environments can generate policy-relevant knowledge. To this end, experimentation was used to examine whether existing regulatory frameworks, such as ISO 13482:2014, adequately addressed real-world safety concerns for exoskeletons (Calleja et al., 2022). In other words, instead of assuming that existing safety standards were sufficient, the key premise was to test them directly in controlled environments, identifying gaps, inconsistencies, and practical oversights that would not be evident without hands-on experimentation.

[13] COVR stands for Being safe around collaborative and versatile robots in shared spaces, and it was a H2020 project, *see* https://cordis.europa.eu/project/id/779966.

[14] *See* https://www.safearoundrobots.com/toolkit/home.

[15] COVR offers a toolkit framework that creates a unified approach to robot safety. *See* https://www.safearoundrobots.com/.

[16] *See* https://www.universiteitleiden.nl/en/research/research-projects/law/propelling.

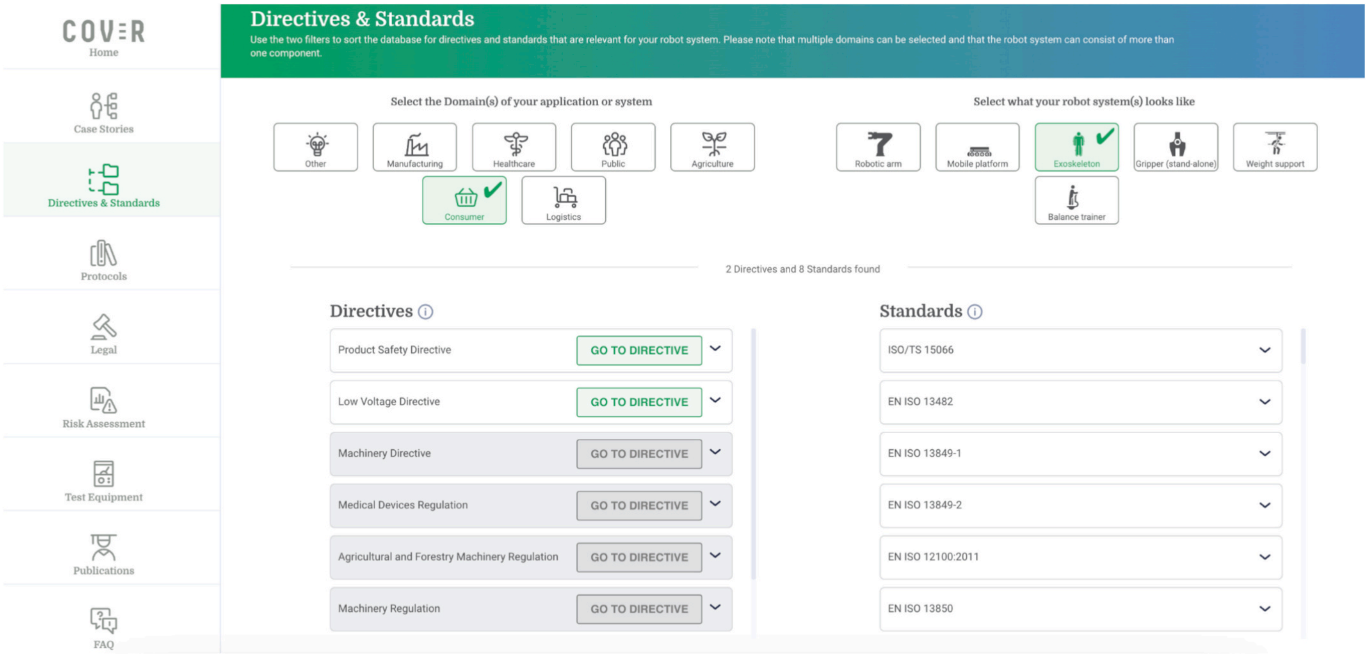

Fig. 3. Screenshot of the COVR Toolkit project that uses the filters 'domain of application' and 'robot system' to sort the database for directives and standards relevant for the robot system.

PROPELLING focused on different key safety concerns for exoskeletons that were either underexplored or completely absent from ISO 13482. In particular, the main results (Fosch-Villaronga et al., 2023b) can be summarized as follows:

1. Fear of Falling (FoF): Exoskeleton users, particularly those regaining mobility after paralysis, experience psychological barriers to trusting robotic assistance. However, ISO 13482:2014 does not classify FoF as a safety hazard or provide guidelines for mitigating its impact. PROPELLING conducted physiological stress testing to measure user anxiety levels, revealing that FoF should be formally recognized as a regulatory concern rather than merely a psychological byproduct of rehabilitation.
2. Protective Stops and Graceful Collapsing: While emergency stop mechanisms are a standard feature in robotics, PROPELLING found that protective stops in exoskeletons were poorly defined in existing regulations. The study revealed that abrupt halts, particularly during stair climbing or walking on slopes, could introduce new hazards, such as fall risks due to sudden loss of balance. These findings suggested the need for clearer regulatory guidelines on how protective and emergency stops should be activated and under which circumstances.

Additional regulatory gaps emerged as experiments progressed. One major realization was that both the robotic systems and the test environments lacked consideration for diversity (Fosch-Villaronga and Drukarch, 2023): the robots, testing protocols, and evaluation criteria did not sufficiently account for differences in user body types, mobility impairments, or intersectional factors such as gender, age, and disability. This oversight raised concerns about equitable access and inclusivity in wearable robot design, underscoring the need for more representative testing methodologies to ensure that regulatory frameworks address safety and usability for diverse populations. The data from these scientific experiments led to concrete revisions being proposed to ISO 13482:2014, the standard that regulates PARs including exoskeletons. It was recommended that ISO 13482:2014 provides manufacturers with more guidance to consider users with different characteristics, including physiological characteristics, when designing exoskeletons (Fosch-Villaronga et al., 2023a, 2023b).[17]

6.3. *Future validation of science for Robot policy*

From an *ex-post* perspective, the question is how the *Science for Robot Policy* model's effectiveness will be assessed. Although it is difficult at this stage to anticipate the effectiveness in mitigating the aforementioned regulatory disconnect, future empirical validation can be in the nature of various qualitative and quantitative methods. In this regard, stakeholder consultation, whereby the views of different stakeholders on the usefulness of the outputs produced by the *Science for Robot Policy* model in improving robotics regulation in the EU are elicited, will be key. The reflexivity of the present researchers in critical reflection and dissemination of the model's outcomes will also be useful. Further, metrics such as the number of peer-reviewed publications generated (in the short-term), the citations received by such publications (in the medium-term), and the replication of the model by other researchers for different categories of robots successfully, e.g. for farming robots or industrial robots (in the long-term), will also indicate the validation of the model. Similar metrics are used to evaluate whether research initiatives such as Horizon Europe create high-quality knowledge that produces scientific impact (EC, 2023-b).

7. Showing the theoretical connections and the research contribution

This paper has outlined the need for a new knowledge production process that reduces the gap between technology and regulation in robotics. In accordance with the CRM method, we now systemize the model's contributions to show the theoretical and practical solutions provided in the law of robotics and regulation theory. By *regulation*

[17] This research received the EU Product Safety Award from the EU Commission,# as it was not only the first time that it was found that women can be adversely affected when implementing exoskeletons, but also that there is a lack of diversity at multiple levels, including standards, testing zones, robot developer teams and science and education.

theory, we refer to the interdisciplinary study of how rules, norms, and governance mechanisms are developed and applied — including legal frameworks, administrative procedures, standard-setting, and informal regulatory tools — particularly in contexts shaped by uncertainty, complexity, or rapid innovation (Baldwin et al., 2011). In this sense, our model constitutes a novel approximation to a well-known problem–regulatory disconnect–in six key contributions.

First, it constitutes a genuine instrumentalization of *Science for Policy*. Although Science for Policy has been deeply discussed and encouraged by the umbrella of European institutions, its practical applicability across different domains remains limited, undermining its effectiveness. By "instrumentalization", we refer to designing a clear framework for translating scientific knowledge into law, ensuring that the model is not just theoretical. Our approach goes beyond theoretical discussions on the theory of regulation, instead proposing a structured method for bridging scientific insights with legal implementation, producing practical output that can systematically inform and improve robot governance frameworks.

Second, while the problem of regulatory disconnect exists across emerging technologies, robotics presents particular challenges that require targeted solutions (Yang et al., 2016). Technology does not only advance linearly but horizontally, introducing new categories of robots that existing regulations struggle to accommodate. As a result, further development and specification of the regulatory framework is needed. The specifics of these require particular considerations. Although the model presented can be generalised, its design has been devised and adjusted to the problems of service robots.

Third, unlike traditional legal research, which predominantly relies on case studies and legal analysis, the Science for Robot Policy model is empirical and experimental, demonstrating how scientific insights can contribute to regulatory refinement. Through developer engagement and by taking an empirical approach, our validated model demonstrates that qualitative stakeholder engagement and quantitative, real-world testing (in a hybrid approach combining compliance, experimentation, and policy feedback loops), can help inform and refine robot policy.

Fourth, the interconnection of methods and techniques used within the model constitutes an innovative way to generate useful knowledge for policymakers. Thus, as indicated, with the proposed interdisciplinary approach —law, science, and robotics— knowledge brokers can effectively generate and synthesize evidence for policymaking in service robotics. By basing these recommendations on rigorous testing, stakeholder engagement, and expert advice, we understandably translate our scientific findings and offer changes that are acceptable and manageable for policy institutions, including ISO standards committees (Bielak et al., 2008; Turnhout et al., 2013; Gluckman et al., 2021).

Fifth, another crucial aspect of the model is its comprehensible and inclusive approach to the agents involved in regulatory processes. There are instances in which *the science for robot policy* model shows the potential to benefit different stakeholders including:

1. Robot developers, who are producing technology quicker than the legal framework, can catch up and can quickly go through the laws and regulations to determine what requirements they must comply with to ensure safe robot design and use.
2. Policymakers will have evidence-based policies, anchored in rigorous scientific testing, to support their legislation. In this way, new regulations can provide adequate safety, be inclusive, and sufficiently techno-specific.
3. End users who use these robots in their daily lives, in schools, hospitals, and homes, will be better protected from safety and other risks currently inadequately addressed in the EU legal framework.

Sixth, this work reinforces the idea that leveraging scientific evidence in policymaking requires an understanding of policymakers' evidentiary needs and ensuring that scientific knowledge generated is aligned with these requirements (Gluckman et al., 2021). In service robotics, this calls for a knowledge broker that can bridge between the gap between the researchers and policymakers, ensuring that users' fundamental rights are respected and protected throughout the lifecycle of robotic technologies.

In addition to these contributions, the model advances a more reflexive understanding of science for policy by embedding *situated knowledge* and *reflexivity* within the evidence-production process. Reflexivity, a concept rooted in anthropology, refers to the continuous critical engagement with one's own position, values, and assumptions in the research process (Palaganas et al., 2017). Within *Science for Robot Policy*, reflexivity applies not only to researchers but also to knowledge brokers, who act as intermediaries between scientific and policy domains. Recognizing that evidence is shaped by social, cultural, and political contexts—such as gender norms, power asymmetries, or institutional logics—knowledge brokers must interpret and communicate findings with transparency and epistemic humility. This awareness strengthens the aspiration for objectivity of the policy recommendations, not by pretending to eliminate subjectivity, but by making its influence visible and accountable (Waheed, 2016; Haraway, 1988). Through this lens, ethical principles are not simply applied to output but are integrated into the *entire evidence lifecycle*, from experimentation and stakeholder engagement to data interpretation and policy translation. In doing so, the model positions itself as both a regulatory and epistemological innovation—capable of guiding inclusive robot policy while remaining aware of its own normative foundations.

Moreover, clarifying the model's theoretical underpinnings and interdisciplinary value reinforces its role as a regulatory tool and a knowledge-producing construct that responds to practical challenges in service robotics governance.

8. Examine the scope of applicability of the solution

Unlike theory-building, constructive research is not about constructing a theory but an approach to finding tangible solutions to practical problems (Eisenhardt and Graebner, 2007). Therefore, assessing the scope and feasibility of the model's applicability and facilitating future refinements are fundamental to the method's core principles (Lehtiranta et al., 2015).

Science for Robot Policy as a working model to reduce the regulatory disconnect in service robotics has internal and external limitations. Internal limitations refer to the validity of the model itself and its capacity to build and test hypotheses for improving the service robot regulatory framework. The external limitations relate to the frictions arising when the model is implemented and link to the set of economic, political, and legal constraints that could jeopardize the successful implementation of the model in a real-world context.

With respect to the internal limitations, our proposal is based on a set of inference techniques that allows us to, starting from the legal framework, generate policy-relevant knowledge. The qualitative and quantitative techniques used in *Science for Robot Policy* have their own limitations, which could compromise the validity of the results obtained. Table 1 presents a summary of limitations associated with each inference technique used and the strategy envisioned to mitigate those limitations.

Several strategies may help mitigate internal limitations and enhance the validity of the findings of the Science for Robot Policy model. Transparency in inclusion criteria can reduce selection bias while expanding sources to include gray literature may provide a broader evidence base. Stakeholder engagement can put findings into practical perspective, making results more policy-relevant, mainly when diverse stakeholders are included to reflect a range of perspectives. Iterative validation and triangulation with diverse data may further enhance reliability, allowing for cross-checking insights from multiple sources. In experimental settings, hybrid research approaches and diverse participant recruitment can improve external validity, increasing the likelihood that findings generalize beyond controlled environments. Finally,

Table 1
Limitations associated with the model.

Step	Technique	Limitations	Mitigation
Risk identification (Step 2)	Meta-analysis: ● Systematic literature reviews ● gray information analysis	● Availability of information ● Publication bias (Alfonso et al., 2024) ● Heterogeneity ● Data dependency	● Transparency in inclusion criteria to avoid selection bias ● Expand the data sources via gray literature ● Stakeholder engagement to put the results in perspective
	Stakeholder engagement	● Limited generalizability ● Social desirability bias (Richard et al., 2020) ● Subjectivity of Interpretation (Guest et al., 2020)	● Diverse stakeholder inclusion ● Iterative validation ● Triangulation with diverse data
Novel-data generation (Step 3)	Experimental design	● Limited External Validity (Kemper, 2017) ● Participant biases ● Lack of control of all variables	● Hybrid research approaches ● Diverse participant recruitment
Policy-relevant knowledge (Step 4 & 5)	Policy formulation	● Bias and subjectivity ● Argumentative fallacies ● Incomplete information	● Cross-disciplinary validation ● Incorporating uncertainty analysis

cross-disciplinary validation may strengthen policy recommendations by incorporating expertise from multiple fields. At the same time, uncertainty analysis can help recognize knowledge gaps, ensuring that regulatory decisions remain adaptable as new information emerges.

External limitations refer to constraints that restrict the model's applicability not due to a lack of internal validity but because of external pressures or limitations. Policy and legal decision-making is often influenced by political considerations, such as electoral cycles, interest groups, and public opinion. Therefore, although the results may be valid, their implementation is conditioned by the political cycle, which constitutes a significant limitation, considering that the aim of *Science for Robot Policy* is theoretical and practical. Given that the JRC acts as the European Commission's in-house science service and it provides scientific advice and technical know-how to support a wide range of EU policies, it is the hope that they would adopt our model for service robotics regulation.

Economic constraints and the availability of infrastructure necessary for executing all stages of the model must be considered. Experimentation implies an important cost factor not only in terms of economic resources but also in time. Additionally, the reproducibility of such experiments is a key aspect that needs to be ensured, which means making an important investment in maintaining the infrastructure necessary to conduct the tests. A key advantage of our model is that our construct is a *modus operandi* model that determines the logical steps to follow from raw data to knowledge, with the ambition of being able to be implemented in already existing experimental structures such as the European Network of Living Labs (EnoLL).

Thanks to the mitigation strategies, *Science for Robot Policy* accounts for some of the limitations and constitutes a state-of-the-art solution to regulatory disconnect in service robotics. As indicated, the mutable character of the model constitutes one of its major strengths. Thus, parallel to technological evolution, the model can be readapted to cope with the new issues that new forms of technology could generate. In that sense, the underlying philosophy of such dynamic evidence-based construct is that it could efficiently generate profitable insights for policy and legal design. In this sense, our approach provides a robust methodology for integrating experimentation and regulation. By engaging with standardization bodies (ISO, CEN, IEEE), forming direct collaborations with the JRC and EC, and advocating for structured regulatory tools like an EU Observatory or Robotics Policy Fellowship, policy-relevant information can be effectively translated into policy actions.

While the Science for Robot Policy model is designed within the EU regulatory culture, its core components—including stakeholder consultation, evidence generation through experimentation, and knowledge translation — are not jurisdiction-specific. However, for successful uptake outside the EU, the model must be adapted to fit national legal cultures, institutional structures, and policymaking norms. Its broader value lies in offering a structured methodology for bridging scientific insight and regulatory design — a challenge shared by many jurisdictions, even if the institutional pathways differ.

9. Conclusions

The absence of a coherent legal framework for service robotics results in policies that lack essential safeguards and lead to fragmented regulations and unclear compliance pathways. Robot developers often struggle to integrate crucial legal considerations into their designs, compromising user safety and leading to the creation of systems that, while compliant with regulations such as the Machinery Regulation, still pose potential risks to users (Alemzadeh et al., 2016). Without a unifying anchor, gaps and dissonances between fragmented regulatory frameworks and the technologies they seek to regulate will persist (Giraudo et al., 2024).

This paper presented a working model –Science for Robot Policy– capable of addressing the regulatory disconnect that service robots pose. This regulatory lag, often described as the pacing problem, underscores the difficulty of balancing early over-regulation with delayed under-regulation as technologies evolve (Fenwick et al., 2016). In this regard, *Science for robot policy* is a model that guides policy development for robotics technologies, identifying gaps and dissonances through input from key stakeholders and conducting tests in experimental settings depending on technology readiness. Using a constructive research approach, we demonstrated how raw data is transformed into actionable knowledge in a structured process that ensures that scientific insights inform regulatory decisions. This transition—from data to information to knowledge—adds layers of meaning and relevance to observations, combining objective empirical findings with subjective expert interpretations to ensure that policymakers have a comprehensive, evidence-based foundation for intervention in robot governance.

The proposed model gathers evidence to demonstrate how technology assessments can lead to policy changes through learning processes solving information asymmetries among developers and policymakers. To that end, researchers and scholars with interdisciplinary expertise in law, science, and robotics can be knowledge brokers in this respect and help facilitate the integration of this model into policymakers' regulatory toolboxes.

The Science for Robot Policy model, through its instrumentalization of science, empirical validation, interdisciplinary collaboration, and stakeholder engagement, offers a structured yet flexible approach to robot governance. By demonstrating that regulatory challenges cannot be solved through theory alone, this work bridges the gap between law and technology, showing that robot policy must be as dynamic and evidence-based as the field it seeks to regulate.

CRediT authorship contribution statement

Eduard Fosch-Villaronga: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mohammed Raiz Shaffique:** Writing – review & editing, Writing – original draft. **Marie Schwed-Shenker:** Writing – review & editing, Writing – original draft. **Antoni Mut-Piña:** Writing – review & editing. **Simone van der Hof:** Writing – review & editing. **Bart Custers:** Writing – review & editing.

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Data availability

The authors are unable or have chosen not to specify which data has been used.

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Eduard Fosch-Villaronga is Associate Professor and Director of Research at Leiden University's eLaw Center. An ERC Laureate, he specializes in the legal and regulatory aspects of robotics and AI, focusing on healthcare, governance, diversity, and privacy. He leads the ERC project "SAFE & SOUND" and contributes to Horizon Europe's BIAS Project on AI diversity in the labor market. Eduard has received the EU Safety Product Gold Award (2023) and serves on ISO committees for robot safety standards. He is also involved in UNCTAD's Consumer Product Safety Working Group.

Marie Schwed-Shenker is a PhD candidate at Leiden University's eLaw Center, researching Law and Robotics (Social Assistive Robots) as part of the ERC StG SAFE & Sound project. Previously, she studied Practical Criminology at Hebrew University and Sociology and Anthropology at Tel Aviv University. Marie's work has focused on ethical issues in youth volunteering and the role of media in radicalization. Her Master's thesis examined stereotypes of female prisoners in media and language's role in group radicalization.

Mohammed Raiz Shaffique is a PhD candidate and researcher at eLaw, specializing in Age Assurance and Online Child Safety. His research is part of the EU's Better Internet for Kids+ initiative and the ERC StG SAFE & Sound project. Raiz is investigating policy-relevant data generated from robot testing zones. He earned his Advanced Master's in Law and Digital Technologies at Leiden University with top honors and authored a book on white-collar crime in India. He also has six years of legal experience and expertise in cyber law and dispute resolution.

Antoni Mut Piña is a postdoctoral researcher at the eLaw Center for Law and Digital Technologies at Leiden University, contributing to the ERC StG SAFE & Sound project. He completed his Ph.D. at the University of Barcelona, focusing on empirical legal analysis and consumer behavior. Antoni's work employs advanced data analysis techniques and has been presented at international conferences. He holds degrees in Law, Business Administration, and Political Analysis, with experience in research on consumer vulnerability and regulatory policies. He has received multiple research scholarships.

Simone van der Hof is a full Professor of Law and Digital Technology at the Center for Law and Digital Technology (eLaw) at Leiden Law School, Leiden University. Her research focuses on the intersection of children's rights and digital technologies, addressing privacy and data protection, economic exploitation, and the right to play. She examines how data collection, tracking, and profiling impact children's privacy, evaluating legal frameworks to enhance protections. Her work also explores the risks of economic exploitation in the digital age, including child influencers, eSports, and unfair commercial practices like dark patterns. Additionally, Simone investigates how digital platforms affect children's right to play, balancing online entertainment's opportunities with concerns over commercialization and safety, ensuring children's well-being in the digital environment.

Bart Custers is Professor of Law and Data Science and Head of eLaw at Leiden Law School, Leiden University. With a background in law and applied physics, he specializes in law and digital technology, focusing on profiling, big data, privacy, discrimination, cybercrime, AI, and investigative powers. An experienced researcher, he has led projects for the European Commission, NWO, and various ministries. Formerly Head of Research at the WODC (Ministry of Justice), he also served as a senior policy advisor and management consultant. Prof. Custers has authored books on profiling, privacy, drones, and bitcoins and coordinates Leiden's SAILS project on AI's societal implications.