Biocomposite: Safe-by-Design for the circular economy

TU Delft

Dit verslag geeft de bevindingen weer van een kortlopend onderzoek naar Safe-by-Design in de context van de circulaire economie. Dit onderzoek richtte zich specifiek op de ontwikkeling een biocomposiet dat bestaat uit grondstoffen uit afvalwater. Dit onderzoek identificeert enkele spanningen rond het veilig hergebruik van afvalstoffen en duidt enkele mogelijke oplossingsrichtingen.

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De huidige productie- en consumptiewijzen zijn verre van optimaal. Eindige, niet-hernieuwbare bronnen dienen als grondstof voor producten met een korte levensduur, die snel op de afvalberg terecht komen. Dit conventionele model van take-make-waste krijgt steeds meer kritiek en de noodzaak van een overgang naar een circulaire economie wordt inmiddels breed gedeeld. De circulaire economie bevordert gesloten productiekringlopen die afval minimaliseren en de levensduur van producten en materialen verlengen. Er is een groot aanbod van veelbelovende innovaties geïnspireerd op circulariteit, maar deze innovaties kunnen alleen slagen op voorwaarde van veiligheid.

Safe-by-Design (SbD), oftewel veilig-door-ontwerp, probeert de risico's van nieuwe technologieën te minimaliseren door in een vroeg stadium rekening te houden met veiligheid. Het idee is dat de veiligheid van een nieuw product kan worden verhoogd als wetenschappers, ontwikkelaars en ontwerpers in een vroeg ontwikkelingsstadium passende, op veiligheid gebaseerde keuzes maken. SbD is relevant voor elke innovatie die nog in ontwikkeling is. Maar er kunnen verschillende strategieën van toepassing zijn voor verschillende sectoren bij het implementeren van SbD. Welke ontwerp strategieën werken dan het beste voor circulaire innovaties waarbij afval opnieuw gebruikt wordt?

In dit onderzoek onderzochten we SbD in de context van de circulaire economie. Concreet richtten we ons op de ontwikkeling van circulaire producten uit teruggewonnen grondstoffen uit afvalwater. Ons onderzoek bestond uit een casestudy: we volgden de technologische ontwikkeling van een nieuw materiaal gemaakt van twee teruggewonnen ingrediënten. Deze ingrediënten zijn cellulose uit toiletpapier gezeefd uit afvalwater en een kleverige substantie die wordt geproduceerd door bacteriën die afvalwater reinigen. In combinatie vormen deze twee ingrediënten een nieuw materiaal: biocomposiet. Dit biocomposiet wordt momenteel ontwikkeld door een consortium van academische en industriële partners. Als de ontwikkeling slaagt, biedt het een duurzaam, circulair en biologisch afbreekbaar alternatief voor conventionele materialen die veel worden gebruikt in de bouwsector.

SbD vraagt betrokkenen om vroegtijdig te anticiperen op risico's en vroegtijdig maatregelen te nemen om deze te voorkomen. In lijn daarmee stelden wij twee onderzoeksvragen. Ten eerste, wat zijn de risico's van dit nieuwe biocomposiet? Ten tweede, in hoeverre kunnen deze risico's vroegtijdig en via ontwerpkeuzes worden aangepakt? Om deze vragen te beantwoorden namen we interviews af met direct betrokkenen bij de ontwikkeling van het biocomposiet. We vroegen hen naar de risico's en onzekerheden en tevens om te brainstormen over relevante SbD-maatregelen. Daarnaast bestudeerden we relevante literatuur, namen we deel aan interne consortiumbijeenkomsten en begeleidden we focusgroep onderzoek.

De eerste uitkomst van ons onderzoek is een overzicht van de risico's en onzekerheden die relevant zijn voor dit nieuwe materiaal. In onze analyse besteedden we bijzondere aandacht aan onzekerheden en hun oorzaken, omdat verschillende soorten onzekerheden een verschillende aanpak kunnen vereisen. Onze tweede uitkomst is een lijst met maatregelen die onze geïnterviewden relevant vonden bij het implementeren van SbD. Suggesties variëren van technische maatregelen die door ontwikkelaars moeten worden uitgevoerd tot maatregelen die de steun van verschillende actoren vereisen. Daar bovenop gaf ons onderzoek een kijkje in de praktische aspecten van een innovatietraject, wanneer zowel kansen als beperkingen in overvloed aanwezig zijn. We vonden uitdagingen die voor veel circulaire innovaties van belang zijn. Deze uitdagingen zijn de onzekerheden die voortkomen uit hergebruik van afvalwater en het gebrek aan flexibiliteit in gevestigde waardeketens. Veilig hergebruik

van afval kan nieuwe verantwoordelijkheden vergen van gevestigde actoren, die niet stroken met hun huidige rol.

Onze bevindingen zijn specifiek voor onze casestudy en deze specifieke innovatieomgeving. Toch roepen ze bredere vragen op over SbD in de circulaire economie en SbD in het algemeen. Hoe kan men ontwerpen voor veiligheid gezien de onzekerheid en openheid van afvalstromen? Onze analyse toonde aan dat afvalstromen vaak variëren van samenstelling, moeilijk geheel te analyseren en blootstaan aan allerlei soorten invloeden uit hun omgeving. Kunnen dergelijke onzekerheden volledig worden weggenomen of kunnen we ze beter maar accepteren? In onze casestudy erkennen ontwikkelaars dat enige onzekerheid over afvalwater onvermijdelijk is. Als reactie daarop streven ze naar maximale veiligheid door zorgvuldig de veilige toepassingen voor hun product te selecteren. Hoewel het geen waterdichte oplossing is, laat deze strategie zien welke soorten keuzes relevant zijn voor SbD, met name: op welke plek kun je onzekerheid het beste aanpakken? Het laat ook zien dat maximale veiligheid niet alleen in het laboratorium of de werkplaats tot stand kan komen, maar moet worden beschouwd in de context van een concrete toepassing.

Daarnaast roepen onze bevindingen de vraag op of SbD moet worden gezien als een puur technische handeling en daarmee als de exclusieve verantwoordelijkheid van ontwikkelaars. Is het, gezien de onzekerheden en beperkingen, redelijk te verwachten dat alleen ontwikkelaars weloverwogen, op veiligheid gebaseerde keuzes kunnen maken en uitvoeren? Uit onze analyse bleek dat ontwikkelaars doorgaans binnen hun eigen invloedssfeer opereren. Ze kunnen alleen keuzes maken die binnen hun bereik liggen en hebben weinig invloed op beslissingen die verderop en/of eerder in de waardeketen zijn genomen. Deze situatie duidt op de grenzen van wat kan worden bereikt via technische ontwerpkeuzes. Het vraagt ook om verschillende soorten SbD-maatregelen, bijvoorbeeld maatregelen die de hele waardeketen omvatten. Dergelijke maatregelen kunnen gericht zijn op communicatie en informatieoverdracht, coördinatie en toewijzing van taken en verantwoordelijkheden, en dialoog tussen actoren.

Ten slotte bracht deze casestudy spanningen tussen innovatie en regelgeving aan het licht. Een eerste spanningsveld heeft te maken met de complicaties die hergebruik van afval met zich meebrengt. Wanneer houdt afval op afval te zijn? Hoe zit het met sporen van gevaarlijke stoffen die zich kunnen ophopen als materiaal wordt hergebruikt? Onze geïnterviewden meldden daarmee samenhangende uitdagingen met de risicobeoordeling en regulering van hun product. Een tweede spanningsveld werd gevonden tussen de waarden veiligheid en duurzaamheid. Een veilig product is niet per se duurzaam, dus dan rijst de vraag in hoeverre je in de praktijk veiligheid wil maximaliseren als dat ten koste van andere waarden gaat. Het vinden van de optimale balans tussen veiligheid en duurzaamheid is niet alleen een ingenieursopgave, maar ook een normatieve vraag voor de samenleving. Daarom is een dialoog nodig tussen beleidsmakers, wetenschappers, ontwikkelaars en burgers.

Public summary

Current modes of production and consumption are far from optimal. They turn finite, non-renewable resources into products that are shortly used and discarded afterwards. This conventional model of take-make-waste is increasingly under criticism with many societies seeing a need for a circular economy. The circular economy promotes closed production loops that minimize waste and maintain products and materials in use. Many exciting innovations are inspired by circularity but, for these innovations to be useful, they need to be safe.

Safe-by-Design (SbD) tries to minimize the risks of new technologies by considering safety early on. It suggests that the safety of a novel product can be increased if scientists, developers and designers make appropriate, safety-motivated choices at early stages of development. SbD is relevant to any innovation that is still under development. Yet, different sectors may require different strategies when implementing SbD in practice. In that case, how could circular innovations derived from waste be made safer, by design?

In this research, we examined SbD in the context of the circular economy. Specifically, we focused on the development of circular products from recovered resources. Resource recovery is a set of technologies that can extract valuable resources from waste for reuse. Our research was organized as a case study: we followed the technology development of a novel material made from two recovered ingredients. These ingredients are cellulose sieved from wastewater and a gluey substance that is produced by bacteria that clean wastewater. When combined, these two ingredients form a new material: a biocomposite. This biocomposite is currently developed by a consortium of academic and industrial partners. If successful, it will provide a sustainable, circular and biodegradable alternative to conventional materials that are used widely in the construction industry.

SbD asks designers to anticipate risks early and to take early actions to prevent them. Similarly, we asked two research questions. First, what are the risks associated with this novel biocomposite? Second, to what extent can these risks be addressed early and via design choices? To answer these questions, we conducted interviews with those directly involved in the making of the biocomposite. We inquired about the risks and uncertainties involved and probed our interviewees to brainstorm relevant SbD measures. In addition, we reviewed related literature, participated in internal consortium meetings and coordinated a focus group study.

The first outcome of our research is an overview of risks and uncertainties associated with this novel material. In our analysis, we paid particular attention to uncertainties and their sources because different types of uncertainties may demand different types of responses. Our second outcome is a list of measures that our interviewees thought as relevant when implementing SbD. Suggestions range from technical measures to be implemented by developers to measures that would require the support of different actors. Even more important, our research provided an inside look into the practicalities of an innovation trajectory at a stage when both opportunities and constraints abound. Eventually, we underscored factors of importance that are shared by many circular innovations. These factors are the uncertainties that come with waste and the lack of flexibility that comes with established value chains. The safe use of waste may require new responsibilities that do not correspond with current roles of actors in the value chain.

Our findings are specific to our case study and its particular innovation environment. Still, they raise some questions about SbD in the circular economy and SbD in general. How should developers design for safety given the uncertainty and open-endedness of waste streams? Our analysis showed that waste streams are often variable in composition, hard to analyze exhaustively and open to all types of inputs from their environment. Can such uncertainties be fully taken away or are they best tolerated? In our case study, developers acknowledge that some uncertainty over wastewater is inevitable. In response, they strive to maximize safety by carefully selecting appropriate applications for their product. While not a watertight solution, this strategy questions what types of choices are relevant to SbD. It also reminds us that safety cannot be solely maximized in the lab or workshop but must be considered in the context of an application.

In a similar manner, our findings further question whether SbD should be seen as a purely technical act and the sole responsibility of developers. In the presence of uncertainties and constraints, is it reasonable to expect that developers alone can make and implement informed, safety-motivated choices? Our analysis showed that developers typically operate within their own sphere of influence. They can only exercise choices that are within their reach and have little influence over decisions that were made upstream and/or at earlier points in time. This situation hints at the limits of what can be achieved via technical design choices. It also calls for different types of SbD measures, e.g. measures that include the entire value chain. Such actions may focus on communication and information transfer, coordination and allocation of task and responsibilities, and dialogue between actors.

Finally, this case study illustrated common tensions between innovation and regulation. A first tension has to do with the complications introduced by waste. When does waste stop being waste? What about traces of hazardous substances that may accumulate as a material is reused? Our interviewees reported similar challenges with the risk assessment and regulation of their product. A second tension was found between the values of safety and sustainability. A safe product is not necessarily sustainable so what exactly do we mean when we talk about maximizing safety in SbD? How far should we go in maximising safety if this clashes with other values? Finding the optimal balance between safety and sustainability is not only an engineering task but also a normative question for society. As such, it will require dialogue between policy makers, scientists, developers and citizens.

Executive summary

Safe-by-Design (SbD) is an approach to risk management that emphasizes risk minimization via appropriate design choices at early stages of technology development. Paradigmatic implementations of SbD can be found in nanotechnology and synthetic biology, i.e. technologies that are still under development and characterized by a high degree of uncertainty. Yet, SbD remains a fluid concept with different fields of practice ascribing different meanings to it. Surely, the aims of SbD (i.e. to develop safer technologies) are desirable but its practice (i.e. its conceptualization and implementation) is often vague. In this project, we examine (the applicability of) SbD in the context of the circular economy, in general, and of resource recovery, in particular. Resource recovery is an emerging trend in wastewater treatment that aspires to extract high-value products from wastewater. Recovered resources and derivatives thereof can offer a much-needed alternative to virgin materials, contributing to a transition to the circular economy.

This research was organized as a case study. Specifically, we followed the technology development of a novel biocomposite material made from recovered ingredients. The biocomposite under investigation combines recovered cellulose fibres (i.e. toilet paper sieved from wastewater) and a novel biopolymer excreted by the microorganisms used by a specific wastewater treatment technology. This biocomposite is currently under development by a consortium of academic and industrial partners. If successful, it could provide a sustainable, circular and biodegradable alternative to conventional composites widely used in the construction and infrastructure sector. Note that the novelty of this biocomposite comes primarily from its novel and yet to be commercialized biopolymer. In effect, the development of the biocomposite is part of an ongoing effort to investigate commercially relevant applications of the said biopolymer.

SbD asks innovators to anticipate risks early and to take early actions to prevent them. Correspondingly, we asked two research questions. Firstly, what are the risks associated with this novel material? Secondly, to what extend can these risks be addressed early and by means of design actions? We addressed these questions by means of literature review, observation and stakeholder interviews. Primary data were collected via semi-structured interviews with internal stakeholders (n= 8) conducted in the period between December 16th, 2020 and January 19th, 2021. The interviews focused on collecting expert views on risks and uncertainties, on identifying opportunities for SbD-motivated interventions and on gauging how SbD is perceived by practitioners. Concurrently, the researcher conducting this work attended eight internal meetings, as organized monthly by the consortium. Finally, we complemented our findings with results from a focus group study on the public perception of this biocomposite.

This research provided an inside look into the realities and practicalities of innovation at a midway stage of technology development, when both opportunities and constraints abound. Our findings challenge the stereotypical view of SbD as a practice of making informed, safety-driven choices that lead to innovations with safer properties. Rather, they point to a complex network of interdependencies across actors and to a range of uncertainties that further impede action. In response, the developers of the biocomposite devise solutions that, in times, tolerate uncertainty and resist the illusion of control. While specific to the characteristics and dynamics of this case study, our findings underscored factors of importance that are shared by most innovations in the field of resource recovery, namely the impact of

wastewater (and waste in general) as a source of uncertainty and the influence of established, multi-actor value chains. Both have implications for the practice of SbD in the context of the circular economy.

Of direct relevance to the safety of circular innovations are the uncertainties associated with waste. How should practitioners who wish to exercise SbD respond to the uncertainty and open-endedness that defines waste streams? Our analysis suggests that waste streams are often unstable, difficult to analyze exhaustively and open to inputs from their environment. Uncertainties associated with waste are thus caused by the variability and complexity of our world and, as such, they may be best tolerated than reduced. In our case study, developers seem to accept that some degree of uncertainty over wastewater is inevitable and that complete control of their feedstock may be unattainable. In response, they actively shift their focus from the design of the biocomposite material to the design of its applications. Rather than engineering risks out, they strive to maximize safety via appropriate choice of applications. While not a watertight solution, this strategy invites us to rethink the scope of design actions relevant to SbD. It also puts into question the somewhat unfortunate obsession of SbD with maximizing safety at the material level and reminds us that safety is a contextual rather than a material property.

In a similar manner, our case study further challenges the stereotypical notion of SbD as a purely technical act and as the sole responsibility of developers. In the presence of uncertainties and constraints, is it reasonable to expect that developers alone can make and implement informed, safety-motivated choices? Our findings indicate that developers operate within their own sphere of influence, exercising the choices that are available to them, trusting the information provided to them, and having little influence over decisions that were made upstream and/or at earlier points in time. This situation hints at the limits of what can be achieved via technical design choices and calls for qualitatively different SbD actions across the value chain, i.e. actions related to communication and information transfer; coordination and allocation of task and responsibilities; and dialogue between actors.

Finally, this case study exemplified common tensions between innovation and regulation. Firstly, the processing of waste comes with known complications for risk assessment and regulation. When does a resource extracted from waste stop being waste? How do we go about traces of hazardous substances that may accumulate as a material is repeatedly reused? Our interviewees reported similar challenges with the risk assessment and regulation of their product and called for actions at the political level. Secondly, significant to the circular economy is the realization that a safe product is not *per se* sustainable. In this context, safety and sustainability appear to be two separate and, in times, conflicting values. Finding the optimal balance between the values of safety and sustainability is not only an engineering task but also a normative question for society. As such, it will require actions and deliberations that go beyond the design and assessment of a single product.

Table of Contents

1 Introduction

Safe-by-Design (SbD) is an approach to risk management that emphasizes risk minimization via appropriate design choices at early stages of technology development (van de Poel and Robaey, 2017; Ministerie van Infrastructuur en Waterstaat, 2018; Robaey, 2018; Ministry of Infrastructure and Water Management, 2019). Paradigmatic implementations of SbD can be found in nanotechnology (Kraegeloh *et al.*, 2018) and synthetic biology (Robaey, 2018; Asin-Garcia *et al.*, 2020), i.e. technologies that are still under development and characterized by a high degree of uncertainty. Yet, SbD remains a fluid concept with different fields of practice ascribing different meanings to it. Surely, the aims of SbD (i.e. to develop safer technologies) are desirable but its practice (i.e. its conceptualization and implementation) is often vague. In this project, we examine (the applicability of) SbD in the context of the circular economy, in general, and of resource recovery, in particular. To this end, we use a case study on the development of a novel biocomposite material made from recovered resources (henceforth *BIOCOMPOSITE, BC*). What may be the meaning of SbD for the production of circular materials from recovered resources and how can we operationalize the concept into domain-specific strategies?

Resource recovery is an emerging trend in wastewater treatment that aspires to extract high-value products from wastewater. Traditionally, wastewater treatment would focus on processing a wastewater stream into a sufficiently clean effluent to be safely disposed to the environment. In the recent decades, however, new approaches and technologies suggest that valuable substances and products can be harvested from wastewater (Villarín and Merel, 2020). These products range from (recycled) water and energy to nutrients (phosphorous P, nitrogen N) to cellulose and biopolymers (Kehrein *et al.*, 2020; Kisser *et al.*, 2020). Resource recovery can be understood as a manifestation of the circular economy for it brings (finite) resources back into the production cycle. The circular economy advocates a departure from linear modes of production and consumption (the traditional take-make-waste model) towards closed loops designed to minimize waste and to maintain products and materials in use (Ghisellini *et al.*, 2016; Kirchherr *et al.*, 2017). While not the only approach possible, resource recovery has certainly a role to play in implementing this vision.

The benefits of resource recovery can be understood from two perspectives: benefits from wastewater treatment and benefits from circular production. Firstly, the economic revenue from recovered resources could make wastewater treatment more sustainable economically. Secondly, circular modes of production are praised for they reduce stress on finite resources, especially those labelled as critical. Recovered materials and derivatives thereof can thus offer a much-needed alternative to virgin materials harvested from non-renewable resources. *BIOCOMPOSITE (BC)* is not directly extracted from wastewater but it uses recovered materials as its constituent ingredients. It combines recovered cellulose fibres (i.e. toilet paper sieved from wastewater) and a novel biopolymer excreted and extracted during wastewater treatment (henceforth *BIOPOLYMER, BP*). As such, *BC* aspires to introduce the benefits of recovered materials into the infrastructure and construction sector as well as to secure a viable market for a recovered resource.

Despite their multiple benefits, innovations inspired by circularity are not by definition safe. This renders a SbD approach relevant and timely. Advancing our understanding on how to operationalize SbD in a domain such as the production of circular products from recovered resources will be of relevance to both practitioners and policy makers. Furthermore, our case study is a peculiar testbed for SbD. *BC* is an innovation in the making and thus open to a SbD approach. Nevertheless, its technology readiness level (TRL 3-5) indicates a somewhat more applied orientation than most paradigmatic implementations of SbD operating at early stages of fundamental research (TRL 1-2). In addition, the *BC* project is situated amidst a partially established, multi-actor value chain and runs parallel to a number of investigations on *BP*. This innovation context may introduce new opportunities and limitations to a SbD approach.

The remainder of this report is organized as follows. Section 2 describes the *BC* case study in more detail and explicates our research questions and methodology; due to the consultative nature of this report, methodological details will be provided in appendixes as appropriate. Core concepts from risk theory and literature are summarized in section 3. Sections 4-6 document our results and analysis, focusing on risks, uncertainties and co-created SbD actions. Section 7 reflects on the implications of these findings and provides recommendations for both internal and external use. Section 8 extrapolates our findings to the circular economy and concludes this report.

2 The BIOCOMPOSITE case study

This project followed the technology development of a biocomposite material produced from recovered ingredients. *BC* is a material in the making and the subject of an independently organized research project running in parallel to the one documented here. The object of our case study is thus both the *BC* material (i.e. its properties and production) and the *BC* research consortium (i.e. its practices and views).

BC is a biocomposite intended for use in the construction sector. Composites are reinforced plastics that consist of two primary components, a polymer and a net of reinforcement fibres. Any of these two components can be either synthetic or natural. Conventional composites are a combination of a synthetic polymer with synthetic fibres. Valued for their high strength and relatively low weight, conventional composites are in mainstream use; they are, however, hard to dispose of while the use of fossil-based ingredients is increasingly under scrutiny (Zini and Scandola, 2011). Biocomposites, on the other hand, consist of at least one natural component; most biocomposites produced today are a combination of a synthetic polymer with natural (plant, animal, or waste) fibres (Zini and Scandola, 2011). Biocomposites are widely used commercially in, among others, the automobile and construction sector. Nevertheless, not all biocomposites are biodegradable while the sourcing of natural fibres may be controversial in terms of land use. *BC* is envisioned as a fully biobased, fully circular biocomposite that is also expected to be biodegradable. It combines recovered cellulose fibres (i.e. toilet paper sieved from wastewater) and a novel biopolymer excreted and extracted during wastewater treatment. *BC* is envisioned as an attractive alternative to conventional composites in terms of both its production and its unique properties. The exact recipe and production process of *BC* are presently under development.

The *BP* biopolymer used for the production of *BC* is in itself a novel material under development. *BP* is extracted from the excess (i.e. left over) sludge of a commercially available wastewater treatment method based on the technology of aerobic granular sludge. Wastewater treatment uses microorganisms to remove pollutants from wastewater. In treatments based on conventional activated sludge, these microorganisms grow in open, flat flocs. In aerobic granular sludge, however, they come together to form spherical granules. *BP* is the polymeric substance that these microorganisms produce as they form granules (*extracellular polymeric substance*, EPS). Technically, the *production* (or excretion) of *BP* is subject to the process conditions required for a successful implementation of this wastewater treatment method; this purification technology is already mature and commercialized. The *extraction* of

BP from granules, however, is a subsequent process introduced as commercial interest in *BP* arose; this extraction technology is presently in its pilot phase. The exact composition of *BP* is under investigation and depends largely on the conditions of its production and extraction. To date, it is known that *BP* is a mixture of proteins, polysaccharides, nutrients, and other substances. In addition to being a recovered biopolymer, *BP* demonstrates additional attractive properties, particularly resistance to fire, that are maintained in *BC*.

Figure 1 provides an illustration of the processes that lead to the production of *BC*. Note that the novelty of *BC* comes primarily from its novel, unique and yet to be commercialized biopolymer. In effect, the *BC* consortium is part of an ongoing effort to investigate commercially relevant applications of *BP* and runs in parallel to other *BP*-oriented investigations. Tables 1 and 2 provide an overview of the actors involved in the development of *BC* and *BP* respectively.

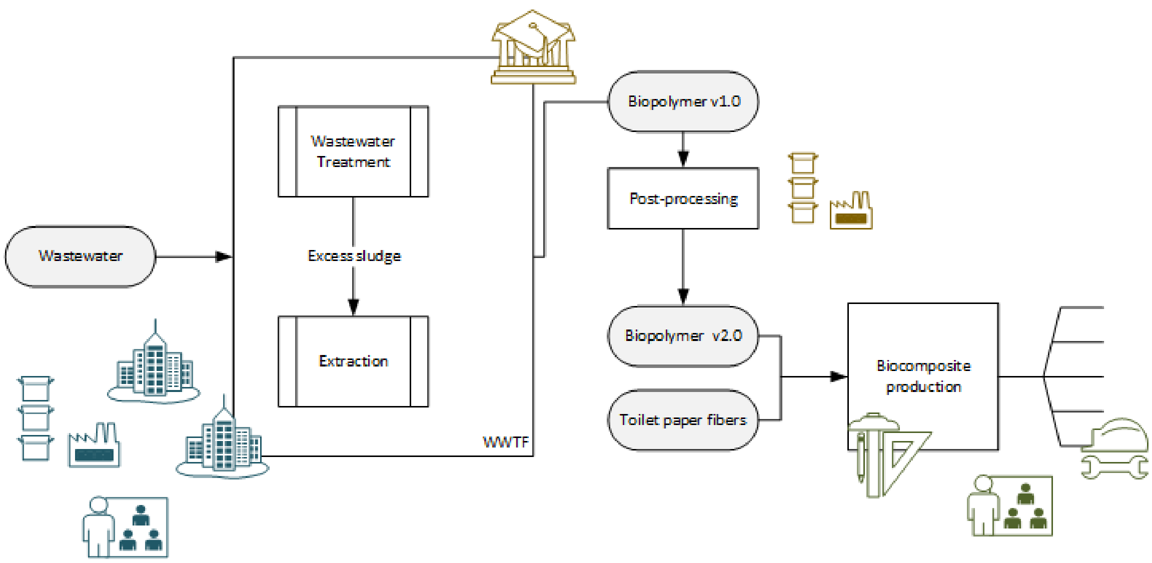

Figure 1: The BC design space. BC is produced at an industrial workshop (bottom right) using recovered cellulose fibers and BP. BP is extracted at a wastewater treatment facility (WWTF) from the excess sludge of wastewater treatment. This crude BP arrives at a post-processing facility and is further sourced to the workshop. In green: partners of the BC consortium; in brown: partners participating in both the BC and the BP consortia; in blue: partners of the BP consortium.

Table 1 Actors involved in the development of BC. NB: Task descriptions represent the actor's role in the ongoing (3-year) BC investigation. Internal: partners of the BC consortium; boundary: partners participating in both the BC and the BP consortia.

Actor	Tasks in the project	Domain	Role	Actor is
Post-Processor	Sources the feedstock biopolymer	Industry	Provider	Boundary
Engineer/Designer	Produces the biocomposite	Industry	Provider	Internal
End User	Building company interested in applications	Industry	User	Internal
Knowledge institution	Conducts fundamental research	Science	Researcher	Boundary
Research institution (1)	Conducts applied research	Science	Researcher	Internal

Table 2 Actors involved in the development of BP. Boundary: partners participating in both the BC and the BP consortia; external: partners of the BP consortium (i.e. external to the BC consortium).

Actor	Tasks in the project	Domain	Role	Actor is
Technology owner	Owns the water treatment technology; expected to commercialize the *BP* extraction technology	Industry	Provider	External
Knowledge institution	Conducts fundamental research	Science	Researcher	Boundary
Research institution (2)	Funds and facilitates research	Science	Funder	External
Post-processor	Expected to market raw *BP* and *BP* end products	Industry	Provider	Boundary
Water authorities	Manage the wastewater treatment facilities; Deploy the pilot extraction installations	Government	User	External

2.1 Aim and methods

To understand the applicability of SbD to the development of a circular material such as *BC*, we asked the following questions:

- What are the risks and concerns of stakeholders regarding future applications of *BC* in the construction sector? ("*what may go wrong?*")
- To what extent can these risks and concerns be addressed early and by means of design? ("*what actions should be taken by whom and when?*")

We addressed these questions by means of literature review, observation and stakeholder interviews. Primary data were collected via semi-structured interviews with internal stakeholders (n= 8) conducted in the period between December 16th, 2020 and January 19th, 2021. The interviews focused on collecting expert views on risks and uncertainties, on identifying opportunities for SbD-motivated interventions and on gauging how SbD is perceived by practitioners; a detailed description of the interview procedure is provided in Appendix 1. Note that those directly involved in the development of *BC* have the knowledge and power to envision SbD actions in this specific context and were thus the target group for our interviews. Concurrently, the researcher conducting this work attended eight internal meetings, as organized monthly by the *BC* consortium. This allowed us to maintain an up-to-date understanding of *BC* and to observe issues of relevance as the *BC* investigation unfolded in time.

Our research shows a strong ethnographic dimension as it draws its conclusions from the opinions and actions of a select community of innovators. Still, we found it useful to supplement our understanding with the perspectives of societal stakeholders. To this end, we coordinated two focus groups on the perception of *BC*, one with technical students and one with homeowners. The focus group study was conducted by a bachelor student affiliated with our research group as part of the student's thesis work. Relevant findings will be briefly discussed here (cf. Section 4.1) while the full report on the focus groups is available upon request.

This work was conducted at TU Delft (NL), Faculty of Applied Sciences, Department of Biotechnology, Section Biotechnology and Society[1]. The study was funded by the Ministry of Infrastructure and Water

[1] https://www.tudelft.nl/tnw/over-faculteit/afdelingen/biotechnology/research-sections/biotechnology-and-society/

Management (in Dutch: *Ministerie van Infrastructuur en Waterstaat*). The *BC* project is funded under the Topsector Energy funding scheme (in Dutch: *Topsector Energie*). The researcher conducting this work was provided access to the proceedings of the *BC* project under a confidentiality agreement.

3 Theoretical framework

3.1 Which risks?

Risk is about a looming danger and the possibility that an adverse effect manifests itself and becomes an unfortunate reality we must deal with. Depending on whom you ask, however, and what their role and stakes in an innovation process are, the nature and range of the envisioned adverse effects vary greatly.

In their investigation the risks of a (then) novel wastewater treatment technology, Zwart *et al.* (2006) observe two different conceptualizations of risk among stakeholders, namely risks *to* and risks *of* the deployment the technology. In the first case, the adverse effect is the failure of the innovation, either in the short term (e.g. an installation becomes decommissioned) or in the long term (e.g. the technology fails to secure a sufficiently large segment of the market). Investigations on barriers and drivers to an innovation also tend to focus on the negative outcome of failure, listing several factors, i.e. hazards *to* the innovation. Let us stress here that concerns about (economic) failure are of core importance to a range of stakeholders and must be taken seriously. Yet, when assessing the safety of a technology, emphasis is typically on the second category, i.e. risks *of*, understood here as potential effects that are detrimental to the health and well-being of humans and ecosystems.

A question typically asked during the risk assessment of a technology is "What may go wrong if we go ahead and deploy the X technological solution in the Y context?" Obviously, what *is* a detrimental effect depends on who is being asked and who is being impacted. Moreover, technical risk assessment focuses predominantly on quantifiable risks, i.e. risks that can be expressed in terms of their severity and probability of their occurrence. It also focuses on impacts that are commonly understood as detrimental (e.g. harms to the health of humans and ecosystems). Yet, the assessment of a technology by various societal groups often includes non-quantifiable impacts or impacts characterized by ambiguity, i.e. effects that we may not yet all agree whether they are negative or not (Swierstra and Te Molder, 2012). Van de Poel (2017) further distinguishes between *physical*, *institutional* and *normative* impacts of a technological innovation, each accompanied by or introducing its own flavour of uncertainty. For the purposes of this text, we will refer to "risks" and "concerns" to capture any adverse effects that may or may not materialize when a technology is deployed. In our interactions with stakeholders, we deliberately refrained from specifying the *types* of risks we inquired about and collected responses that span risk types and risk groups.

3.2 Risk, uncertainty, and ignorance

Even in its most technical sense, risk is by definition associated with a degree of uncertainty: the envisioned adverse effect may or may not manifest in practice. Nevertheless, making assessments about the future impacts of a technology is unavoidably subject to additional (and potentially more problematic) flavours of uncertainty.

Limitations in human understanding and awareness affect our capacity to predict or assess the impacts of a technological intervention. Specifically, there are risks we are aware of and are able to assess ("known knowns"), risks we are aware of but are not (yet) able to assess ("known unknowns") as well as risks we are simply not aware of ("unknown unknowns"). Popularized as the "Rumsfeld factor", due to a 2002 quote by the former US Secretary of Defence, this distinction has appeared earlier in literature in similar or comparable formats. Kerwin (1993), in a discussion on medical uncertainty, identifies six "lands of ignorance": known unknowns; unknown unknowns; errors/false "truths"; tacit knowing; taboos; and denial. The distinction between risks we can attach probabilities to ("risks") and those we cannot ("uncertainties") was made by F. Knight already back in 1921 (Knight, 1921). Several scholars (Wynne, 1992; Walker *et al.*, 2003; Felt *et al.*, 2007; Riesch, 2012; van de Poel and Robaey, 2017) propose comparable gradations of uncertainty that end with our incapacity ("ignorance") to predict every effect of an intervention. For the purposes of this text, we use the word "risk" in its most generic sense to refer to an envisioned adverse effect; the assessment of a foreseen risk (i.e. the assessment of the probability and severity of the adverse effect) can be known, knowable or unknowable. We also use the word "uncertainty" in its most generic sense to describe the condition of not being fully certain, as in not fully knowing (yet) or not being able to decide (yet); this means that we do not limit the use of the term to a strict taxonomic category and that uncertainty can coexist with risk. Finally, we use the term "ambiguity" to refer to multiple and potentially conflicting framings and evaluations of the same issue.

An important aspect of our dealings with uncertainty is the reason *why* we are uncertain at the first place. This is what Van Asselt and Rotmans (2002) call *source* of uncertainty and what Walker *et al.* (2003) call *nature* of uncertainty. Typically, a distinction is made between uncertainty due to lack of knowledge (*epistemic* uncertainty) and uncertainty due to the variability (of our world) (*aleatoric* or *variability* uncertainty). We will return to this distinction in our analysis of uncertainties associated with *BC* (cf. Section 5).

4 Known risks of recovered materials

SbD requires us to ask the "what may go wrong" question early on. It asks us to anticipate reasonably foreseeable risks and take actions to prevent them. In this section, we compile a first overview of the risks and concerns that may be associated with *BC*.

4.1 Overview of risks associated with *BC*

Table 3 summarizes risks and concerns as derived from literature on resource recovery (Diaz-Elsayed *et al.*, 2019; Kehrein *et al.*, 2020; Kisser *et al.*, 2020; Villarín and Merel, 2020), recycled water (Salgot *et al.*, 2003; Toze, 2006; Fielding *et al.*, 2019), biosolids (Beecher *et al.*, 2004; Lu *et al.*, 2012), and bio-composites (Vilaplana *et al.*, 2010) and as identified by our interviewees (cf. Appendix 1).

Table 3 suggests that the *BC* consortium is keenly aware of the known risks associated with their product, without obvious blind spots in comparison to the literature[2]. Still, it is plausible that this overview is incomplete and that the consortium's anticipation of risks would benefit from consultation with other stakeholder groups. Within this investigation, we have only been able to confirm that many of the abovementioned risks are shared by societal stakeholders. Results from two focus groups indicate that technical students and homeowners raise comparable concerns over the feasibility and degradation of *BC*. These groups voiced repeated concerns over the leaching of dangerous substances, e.g. in the soil or in the home environment, and question the degradation of the material due to time, weather conditions or fungal activity. Furthermore, focus group participants discussed the quality, appearance

[2] Although we cannot exclude that interviewees prepared for their upcoming SbD interviews, several safety related actions were implemented or initiated prior to any interactions with the SbD researcher.

(colour; texture) and smell of the material as determining factors for the acceptance of different applications. Homeowners in particular were concerned about the ease of home repairs or DIY interventions and about replacement costs, should a need for replacement arise prematurely. Issues related to economic sustainability (e.g. pricing, competition) and environmental sustainability (e.g. the recycling of the material) were also mentioned. Noticeably, risks associated with wastewater or wastewater treatment did not emerge during the focus groups conversations. This may be due to the limited technical information provided to the participants or because both groups considered the origin of the material to be unproblematic to them.

Table 3 Identified risks and concerns. Literature review: Risks typically associated with recovered materials; may or may not apply to this case study. Stakeholder interviews: Risks anticipated by the interview participants (cf. Appendix 1.4); a mention of a risk does not necessarily imply that the risk is high, only that it is deemed relevant. A square bracket indicates that the risk or concern is raised under different terminology.

	Method		**Risk applies to**		
	Literature Review	**Stakeholder Interviews**	**Workers**	**Users/ Consumers**	**Communities/ Ecosystems**
Contamination					
Contaminants – Pathogens	+	+	+		
Contaminants – Heavy metals	+	+	+	+	+
Contaminants – Other	+	+	+	+	+
Microbial growth during storage		+	+		
Unsafe operation					
Malfunction; unreliable operation	+		+	+	+
Fumes during production		+	+		
Toxic derivatives during reaction		+	+		
pH crude biopolymer		+	+		
Feasibility					
Strength		+		+	
Smell	+	+	+	+	
Appearance	+	+	+	+	
Degradation					
Due to time	+	+		+	
Due to microbial or insect activity	+			+	
Due to water absorption		+		+	
Residues/ Emissions	[+]	+		+	+
Public perception					
Societal acceptance	+	+		+	
Sustainability					
Ecological	+	[+]			+
Economic	+	+			
Societal	+	[+]	+	+	+

4.2 In detail: Risk anticipation in the *BC* consortium

According to the interview responses (cf. Appendix 1.4), the most frequently discussed risks are the presence of contaminants and the issue of public perception. Pathogens and heavy metals receive more mentions, as more is known about these pollutants than about emerging ones. *BP* is seen as the major source of contaminants, while two interviewees expressed additional concerns about the recovered cellulose. The risk of pathogens is expected to be negligible for consumers but relevant to those who handle the material while traces of heavy metals are expected to remain in the final products. With regard to societal acceptance, concerns stem from both the product's origin (i.e. wastewater) and its aesthetics (i.e. unattractive color and smell). Smell is typically associated with public perception; a few interviewees, however, discuss smell not only as an unattractive feature but also as a signal of potentially harmful emissions. Business risks to the *BC* innovation, when explicitly mentioned, refer to either societal acceptance or the material's capacity to meet market demands in a competitive manner.

Below, we briefly examine the identified risks per distinct stage of the life cycle of *BC*:

- *Production*: As said, pathogens and heavy metals pose risks to workers handling *BP* during production. Concerns over pathogens arise not only due to the origin of *BP* but also due to its tendency to spoil while in storage. Next, the safety of workers is central in risks associated with unwanted toxic emissions or reactions. Examples were provided in relation to both *BC* (what fumes are released during production?) and *BP* (what is being formed if we bleach *BP*?). The example of bleaching also indicates a potential **conflict in safety aims**: minimizing concerns associated with appearance and public perception may result in a more hazardous processing (i.e. bleaching)[3]. Finally, some practicalities of the work environment were noted. Consider as an example the practicalities of working in an open, shared workshop or the observation that the chemical industry is not used to working with hazards of biological origin. By contrast, challenges in the processing of *BP* by industrial users (c.f. acidity of crude *BP*) were understood to be within common industrial practices.
- *Use*: Assuming that a safe *BP* is provided, concerns over the safe use of *BC* are typically associated with its mechanical properties. Firstly, *BC* must be fit for use: Is it strong enough for its designated application? Is its performance acceptable? Secondly, *BC* is subject to degradation of its properties due to time and/or environmental factors. Water absorption was pointed out for *BC* is reportedly hydrophilic by nature. Note that specifying acceptable performance targets for *BC* is clearly a **contextual** question. For the majority of interviewees, the chosen application context will define the performance targets and desirable properties of the material. This holds true not only for mechanical properties but also for other safety-related targets (e.g. acceptable level of contaminants).
- *End-of-life*: When probed about risks relevant to end-of-life, interviewees tend to focus on the biodegradability of *BC* with one interviewee mentioning ongoing studies on recycling options. This may imply that the waste management of *BC* is seen of less concern or that *BC* is not expected to be reused. With regard to biodegradability, concerns over residues were raised but most interviewees expect that *BC* will be harmless and describe *BP* as essentially non-toxic at the chemical level. Still, two interviewees noted complications related to **accumulation**.

[3] A conflict in safety aims was also highlighted by another interviewee in relation to regulation: stricter regulations on fire resistance might increase safety for consumers but revive the use of materials that are harmful to workers.

Hazardous residues in very low concentrations may accumulate over time or due to large-scale use, either in the environment or in closed production loops. Both interviewees acknowledge that accumulation complicates the assessment of their product and observe that dealing with impurities may be unavoidable in the circular economy.

5 The many faces of uncertainty

The *BC* technological product is accompanied by several uncertainties customary to its R&D stage. For example, it is reasonable that the *BC* developers do not fully know yet *how* to produce a viable product. After all, this is the aim of the ongoing *BC* investigation. Similarly, the *future* of this innovation (and investment) is also uncertain: *BC* is a high-risk, long-term project with an uncertain outlook and not yet secured outlet market. Such uncertainties are routine to research and innovation and will not be examined further. Here, we focus on additional uncertainties of direct relevance to safety and SbD, i.e. uncertainties over the impacts of this innovation or uncertainties that affect our capacity to act upon its safety.

Why should an investigation on SbD be interested in uncertainties? As said (cf. Section 3.2), our capacity to make assessments over the safety of an innovation is problematized by uncertainties. Thus, to *anticipate* an innovation's impacts is also to consider the uncertainties at work. Moreover, uncertainties are tightly related to (our capacity for) action. They may block action or may require action. We suggest that different types of uncertainties would require different types of actions by different actors. A detailed understanding of uncertainties at work could thus inform our SbD efforts to *respond* to anticipated adverse effects. It may also help us identify *who* is responsible and capable to take action when dealing with specific types of uncertainty.

5.1 Uncertainties associated with *BC*

Figure 2 summarizes the uncertainties identified in the *BC* system. Findings are based on our interviews (c.f. Appendix 1.5 for a selection of representative quotes) and mapped according to the frameworks proposed by Van Asselt and Rotmans (2002); Van de Poel (2017).

	Impact	**Institutional**	**Normative**
Epistemic	Risk Assessment BC Environmental Risk Assessment (ERA) BC BP (composition) BP (production)	Risk assessment framework BP	
Variability	Wastewater		Regulatory framework BC

Figure 2: Identified uncertainties mapped according to their source and associated impacts. This overview includes only uncertainties of direct relevance to SbD, i.e. uncertainties over the impacts of BC or uncertainties that affect the consortium's capacity to design for safety. BP: biopolymer; BC: biocomposite. NB: The word uncertainty is used in its most general sense to refer to the condition of not being fully certain (as in not fully knowing or not being able to decide).

5.2 Epistemic uncertainty: *BP* as a black box

The *BP* biopolymer emerges as the most uncertain and uncontrollable aspect of the *BC* system. Obviously, the future of *BC* is tied to the future of *BP*: without a safe (and certifiable) *BP*, a safe (and certifiable) *BC* is not achievable. Moreover, *BP* is a source of substantial unknowns in the development of *BC*. Firstly, it is generally acknowledged that *BP* is an *unknown* compound*,* the exact composition of which remains under study. Secondly, interviewees closer to the production of *BC* remark that *BP* is *inconsistent* both for reasons of variability and for reasons of unpredictability. They observe noticeable differences in the composition of different batches and in the way different batches behave during a reaction. This is in stark contrast to conventional feedstock, which is well defined and fully known chemically. Lack of knowledge and lack of consistency result in a situation where the developers of *BC* have to make design choices without a full grasp of *BP's* composition and/or behavior. To complete the picture, the production of *BP* is a process that operators do not fully control or steer yet. This may or may not change in the future but, in the present circumstances, the *BC* developers have to use the biopolymer *"as it is"* and without much control over what they receive. In conclusion, *BP* is to be used as a **black box,** understood here as a component the inner working of which are not known**.**

On the one hand, the uncertainties introduced by *BP* could be understood as epistemic: More (fundamental) research should provide us with more information and, subsequently, with more control over the biopolymer and its use as a feedstock in biocomposites. Interviewees closer to the production of *BC* express a clear need for more information on *BP's* composition and safety. In theory, these *information needs* could be addressed by means of more research[4]. On the other hand, *BP* is a substance that is synthesized indirectly, i.e. by means of a microbial community. In the future, *BP* is also expected to be produced from a relatively unstable source, i.e. municipal wastewater, and at multiple locations. It is therefore possible that *BP* remains a variable feedstock, with variations in its structure (i.e. in the chain of the polymer) or in its total composition (i.e. in the concentrations of compounds present). It remains to be seen whether the production process of *BC* can correct for this variability. After all, biobased feedstock are notorious for their variability while exhaustive knowledge about the composition or production of a natural substance (e.g. wood) is not a prerequisite for its use.

5.3 Variability uncertainty: The sewage as an open system

Municipal wastewater and the sewage system in which it circulates constitute the second major source of uncertainty. The sewage is described as an **open system** that cannot be fully known or controlled. Potentially problematic or unsafe substances can be introduced easily into the system, as illustrated by the example of paint being thrown down the sink. Thus, there is always a possibility of a problematic substance finding its way into wastewater and, eventually, into the final product. This situation has three immediate implications. First, we can never (fully) *know* what's in there. Second, we can never (fully) *control* what's in there. Third and consequently, we can never *guarantee* that there is no risk, even if the risk is very small. This inherent characteristic of the *BC* system has implication for the safety of the material and its future use.

[4] In the course of the *BC* project, one academic partner became incorporated into the company producing *BC*. This seems to have enhanced the company's access to resources and equipment, with the *BC* developers eventually confirming some of their intuitions. Parallel developments in the *BP* consortium produced additional data on *BP*'s composition; however, *BC* production may not have benefited yet from these advances.

The uncertainties introduced by wastewater are related to technical limitations, as we are simply unable to continuously perform an exhaustive analysis of the wastewater contents. As very poignantly said by one of our interviewees, when one deals with hazards in waste, one cannot expect an exhaustive analysis but must know in advance what to look for. Besides, knowing *exactly* what's in there will not get us any further unless we have a risk assessment in place for all the compounds identified. Analytical challenges aside, the entry points to the sewage system will remain out of our control. Moreover, unanticipated events (e.g. a global pandemic) are likely to find an immediate outlet into this system as wastewater seems to be connected to every aspect of our everyday life. To sum up, the uncertainties introduced by wastewater require us to accept that we are dealing with an open, variable and complex system that resists control.

5.4 Institutional uncertainty and normative ambiguity: Which safety?

Uncertainties related to the risk assessment and regulation of *BC* and *BP* come in various shades. Consider for example gaps in the risk assessment of municipal *BP* and of *BC*. Data on the concentrations of known contaminants are still being collected for municipal *BP* while the biodegradability of *BC* (including its environmental impact) is still under research. These epistemic uncertainties are reasonable given the project's stage and maturity with interviewees being optimistic about fulfilling current regulatory requirements in respective applications. Then again, the existing regulatory framework may be incomplete, inconvenient, inappropriate or outdated. Corresponding issues may be best understood as institutional uncertainties about how to regulate these novel recovered materials. Several examples were provided:

- *No standards for emerging contaminants:* Interviewees are optimistic about meeting current regulatory requirements on known contaminants per specific applications. Yet, *which* contaminants are relevant in *which* concentrations is an open and complex question. For example, standards on emerging contaminants (e.g. microplastics; relevant to the regulation of biodegradable biocomposites such as *BC*) or contaminants in very low concentrations (e.g. PFAS; relevant to *BP* and *BC* as PFAS may enter the sewage via dishwashing) are reportedly not available. Noticeably, this is seen as both a scientific problem and a political one.
- *No or inappropriate standards for (chemically) novel materials*: The unique and unprecedented nature of *BP* corresponds with a lack of standards, criteria or frameworks for it. Interviewees closer to the development of *BP* discuss the challenges of 1) obtaining an end-of-waste status in the absence of established end-of-waste criteria and 2) registering the biopolymer as a chemical substance in REACH in the presence of requirements based on conventional, oil-based polymers which reportedly make little (chemical) sense for biopolymers. Inappropriate requirements are seen not only as troublesome to comply with but also as failing to capture what is truly relevant to the safety of biopolymers.
- *Inconvenient standards for nascent materials*: *BC* is a nascent product without a track record. This complicates the assessment of its life expectancy and of its long-term impacts. Interviewees closer to the production of *BC* refer to safety standards based on conventional materials (e.g. steel) and further explain that developers of new materials are unable to provide data on health effects from long-term exposure. Oftentimes, it is remarked that safety is used as an argument to keep innovative materials off the market while one interviewee described a prevailing risk culture that is less tolerant to newly introduced risks.

Let us stress here that the *BC* and *BP* consortia do not in any capacity exploit the abovementioned institutional uncertainties. On the contrary, they emphasize that blindly complying with regulations is not the way to go when it is obvious that these regulations are unsuitable. Moreover, the *BP* consortium is actively drafting a proposal for a suitable risk assessment framework for *BP*. That said, resolving institutional uncertainties remains the responsibility of government. Governmental and regulatory bodies are typically referred to as both *overseers* who specify safety targets and as *referees* who ensure compliance. In times, they are also described as *partners*, with interviewees welcoming an exchange between companies and regulators, e.g. when deciding what risks we can afford to take.

We conceptualize the above uncertainties over safety standards and frameworks as institutional ones. Yet, safety standards also indirectly prioritize and institutionalize *what* we conceive as safety. We suggest that uncertainties over a commonly agreed definition of safety go beyond (institutional) uncertainty. Consider as an example the ambiguous relationship between safety and sustainability. Remember that *BC* is a biobased material produced from recovered resources, aspiring to become a sustainable and renewable alternative to fossil-based construction materials. For some interviewees, sustainability is thus a core value that may in times conflict with the value of safety. Some question whether safety in SbD (i.e. the safety we strive to maximize) includes or should include sustainability. One interviewee in particular made a point about short-term and long-term safety, the former being measured in deaths from direct exposure and the latter being measured in deaths due to catastrophes related to climate change. The question of *what* constitutes safety will have multiple answers depending on the values we wish to prioritize as a society and is thus best conceptualized as normative ambiguity. Acting upon such a normative ambiguity will require deliberations that go beyond the design and assessment of a single technological product.

6 SbD actions in the context of *BC*

Having collected risks, concerns and uncertainties associated with *BC*, we now turn to the question of SbD actions. To what extend can the identified risks be addressed early and by means of design? What actions should be taken by whom and when? In this section, we discuss the solutions envisioned by our interview participants, i.e. the actors directly involved in the development of *BC* (cf. Appendix 1).

6.1 SbD actions proposed by interviewees

All interviewees but one report being unfamiliar with SbD. Nevertheless, they were all able to comment upon the SbD cards (cf. Appendix 1.3) and to identify or envision SbD actions related to the development of *BC*. The most frequently chosen SbD cards were *hazard elimination* and *prevention via design choices*. *SbD as a core value* triggered mixed responses while the benefits of *early anticipation/ early stakeholder involvement* were discussed in general but not in direct relation to safety.

Table 4 summarizes the SbD actions proposed by our interviewees. Many actions coincide with existing safety measures, i.e. actions already implemented and recognized as pertinent to a SbD approach. Other actions refer to potentially relevant measures brainstormed by our interviewees in the context of SbD. Note that listed actions were generated as interviewees reflect upon the notion of SbD. For this reason, they do not capture all safety-related efforts taken by the consortium, only those perceived as SbD.

Table 4 SbD actions generated by interviewees and corresponding moments of intervention. Actions in square brackets [] were brainstormed in the context of SbD but are not yet implemented; actions without square brackets are already implemented and recognized by interviewees as pertinent to SbD. BP: biopolymer; BC: biocomposite. NB: While no concrete SbD actions were proposed at the disposal of BC, actions taken at earlier stages should in theory help against risks encountered at that stage.

		***BP* Extraction**	***BC* Production**	***Product* development**	***Product* use**	***Other/* n.a.**
Sanitation step extraction	We kill pathogens during the extraction process	+				
Choice of additives	We only use natural, non-toxic additives		+			
Appropriate applications	We choose applications that minimize the risks			+		
[Monitor]	We should monitor the material over time				+	
[Prototype]	We should build incremental prototypes			+	+	
Industrial instead of municipal	We (could) use *BP* from industrial wastewater	+				
[Dedicated step for heavy metal rich wastewater]	In case of a wastewater rich in heavy metals, we could introduce a dedicated step for their removal	+				
Remove impurities at recycling	We should remove impurities during recycling/ waste processing	+				
[Low storage time]	We could minimize the storage time of *BP*	+	+			
High temperature production process	High temperatures during the production process should kill pathogens		+			
[Reinforce in a sandwich panel]	We could reinforce the material by placing it in-between two layers of stronger material		+	+		
[Education]	We could introduce SbD in the curriculum					+
Good team	A good team can make balanced risk decisions					+
[Inventory of risks]	We should have an inventory of relevant risks					+
[Inventory of solutions]	We should have an inventory of existing solutions					+
Safety sheet	We should have a safety sheet		+			

Most of the above actions represent a **technical design** choice that would typically fall under the responsibility of the practitioners (scientists and engineers) involved in the project. In line with the interviewees' roles, the proposed measures apply predominantly to the production of *BC* and to the extraction of *BP* (i.e. from existing excess sludge). While no concrete SbD actions were proposed at the disposal of *BC*, actions taken at earlier stages should minimize risks encountered at that stage, at least in theory. In addition to technical design choices, a few actions correspond with measures at the **organizational level** (education; good team) while others relate to **information needs** and decision making support (safety sheet; inventory of risks; inventory of solutions).

Proposed measures may contribute to an overall increase in safety or may tackle specific known risks (cf. Appendix 1.6). Several solutions address the hazards of pathogens, contaminants and other toxic ingredients which are to be avoided (*choice of additives*) or eliminated (*sanitation step extraction*) to the extent possible. Technically, this is achieved via substitution (cf. inherent safety principles as formulated in Amyotte *et al.* (2009)) or process optimization. As one might expect, these technical actions aim to maximize safety as a material property of the final product. After all, *BP* ad *BC* do not exist without careful design choices. Yet, the collected SbD actions also suggest a broader take on how to maximize safety, e.g. via product design (*appropriate applications*) or via iterative learning (*monitor*; *prototype*). These actions also appear to be explicitly oriented towards uncertainties as opposed to known risks.

Finally, it is worth mentioning that *BC* in itself is partly understood as a SbD effort. Most interviewees perceive recovered materials as a worthy cause that will increase safety both in the long term, by meeting sustainability aims, and in the short term, by replacing fossil-based materials with less harmful alternatives. The production of biopolymers was also reported to be safer than the production of conventional plastics. In that sense, the notion of SbD as a quest for safer alternatives (SbD card *innovative hazard elimination*) was somewhat redundant.

6.2 SbD as mediation: Appropriate applications

Several interviewees respond to the SbD objectives by shifting focus from the design of the material to the design of its applications. Rather than aiming to engineer risks out, interviewees suggest aiming for applications where the current properties of the material would not pose a significant risk. This is mainly expressed in terms of avoidance: Avoid applications where users come in direct contact with the material, avoid application where the material is visible, avoid applications where specific contaminants are a red flag, avoid sensitive application domains. Finding the right application for the right material is a basic engineering task but it important to clarify here that our interviewees overtly propose this as a SbD strategy. The strategy is suggested as a preventive measure against both physical risks (i.e. use the material where it is less likely to cause harm) and risks associated with public perception (i.e. use the material where it is less likely to be perceived negatively).[5]

Arguably, the domain of SbD tends to favor safety as a material property despite its obvious contextual and relational dimensions (Schwarz-Plaschg *et al.*, 2017). It is thus noteworthy that our interviewees approach safety as something to be achieved or maximized at the level of applications. We suspect that the objectives of the consortium (i.e. to find feasible applications for *BP* and *BC*) have played a role. Furthermore, our interviewees are aware of the limitations of their material and investigation: there is only so much one can achieve with *BP* "as it is" and there is only so much one can control with municipal wastewater. We hypothesize that the specific uncertainties associated with *BC* may have encouraged the designers to let go of fully controlling the material properties of their product and to focus instead on what they can influence, namely the context of use. In doing so, they effectively opt to tolerate uncertainty as an inevitable reality one must design for.

The question of *what is* an appropriate application risk-wise is not easy to answer. Temporary outdoors applications (e.g. temporary support structures for plants) are positively discussed for they both minimize risks associated with strength or degradation and make the most of the biodegradable qualities of the material. Then again, outdoors applications pose a higher risk in term of containment,

[5] Obviously, a measure such as *appropriate applications* can only minimize physical risks for the users of a product, not for those tasked with producing it. Nor can it protect future circular practices from the accumulation of hazardous substances. Still, this strategy is notable as a measure against the *possibility* of unanticipated hazards, rather than against confirmed hazards.

should a problematic compound be traced in the material. Similarly, indoors applications are positively discussed for they have low structural demands and can benefit from the fireproof properties of the material. Then again, concern about bad smell in indoors settings are also voiced. Finally, anything related to food (food packaging, utensils, etc.) is considered sensitive and to be avoided.[6]

6.3 SbD under constraints: Industrial vs municipal wastewater

The *BP* presently used in the *BC* investigation is of industrial origin (i.e. using wastewater from a cheese processing facility). For now, the use of *BP* of industrial origin effectively protects those developing *BC* from certain risks, namely risks from contaminants. Arguably, a SbD approach would also dictate that the most benign wastewater is used for future production. Yet, despite the safety advantages of industrial wastewater, the *BP* and *BC* consortia ultimately aim to produce and use biopolymers from municipal wastewater. This is predominantly for economic and practical reasons, such as the volume of municipal wastewater. Recovering resources from municipal wastewater is certainly a relevant objective. However, it introduces an obvious constraint to SbD efforts: using municipal wastewater is a (non-negotiable) given that introduces a ceiling to what can achieved in terms of risk minimization. On a side note, a safer wastewater stream may be an obvious choice from the viewpoint of SbD but it was also criticized by one interviewee as a half-measure. According to this interviewee, impurities (such as the ones present in municipal wastewater) are unavoidable and bound to accumulate in any circular system. Therefore, finding solutions that make a problematic waste source safer would be more beneficial than switching to a less problematic waste source.

The presence of a constraint such as the use of municipal wastewater has direct implications for SbD. Firstly, our study reaffirms that choices in the real world are motivated by various reasons, not only by the pursuit of safety. Secondly, it is obvious that not all design choices will be available to the designer at the time of development. Some choices may be non-negotiable while others may fall under the responsibility and interests of different actors along the chain. This was observed in the use of municipal wastewater (which is a given) but also in the use of *BP* (which is provided as it is). As a result, all actors operate within their own **sphere of influence**, exercising the choices that are available to them, trusting the information available to them, and having little influence over decisions that were made upstream and/or at earlier points in time. These prior decisions may or may not have been made with safety in mind or with sufficient information at the time.

Our interviews revealed multiple examples of this **compartmentalization** of the design process. Polymer scientists felt limited in their capacity to optimize the biopolymer because they work with the excess sludge of wastewater treatment ("the waste of the waste"). Post-processors felt limited in their capacity to optimize the raw biopolymer because the extraction protocol is already fixed. Material scientists felt limited in their capacity to optimize the biocomposite because the feedstock biopolymer is what it is. Existing infrastructures, existing agendas, role distribution and lack of fundamental knowledge are some of the factors that seem to affect one's subset of design choices. The same factors may prompt developers to prioritize choices that do not require changes upstream instead of communicating emerging requirements to upstream actors.

[6] Results from two focus groups indicate similar reasoning among homeowners and technical students, with containment being an argument against outdoors applications. Still, low structural outdoors applications in public space seem to be preferred for being easier to monitor.

7 Discussion

7.1 What can *BC* learn from SbD?

The *BC* consortium emerges as particularly attentive to the factors that would affect the success of their final product, safety and public perception included. Furthermore, the consortium partners have considerable experience in certifying novel materials and are well-acquainted with safety standards. In addition to adhering to "standard" safety practices in their field, these partners are also committed to safety in the broader sense of contributing to safer and circular materials and materials flows. Then, what can the *BC* consortium learn from SbD?[7]

7.1.1 Explicate your safety commitments

Approaching *BC* with a SbD lens can certainly benefit the *BC* project in terms of **awareness**. Consider as an example the *choice of additives* in the *BC* recipe. Interviewees often describe this measure as an implicit choice or as a choice suited to the spirit of their project. SbD can provide a more explicit framing for this choice and help bring already made commitments to the foreground. This can be profitable both in terms of competitive positioning and in terms of adherence to these decisions during development[8]. In a similar manner, several interviewees talked about safety as an implicit part of the job or something that is "always at the back of our heads". We suggest that a SbD frame can help systematize the ongoing efforts, support the developers in what they already do well, and prevent any slips or omissions. In practice, this may require small but significant changes such as making safety part of the agenda both in internal meetings and communications and in interactions with external stakeholders[9].

The *BC* consortium is on its way to generating data required for the assessment of known and anticipated risks. In the case of *BC*, anticipating risks as part of a SbD approach did not reveal significant new risks. However, a SbD lens may inspire the consortium to navigate these known risks differently. Consider as an example material attributes associated with public perception, such as smell or appearance. We suggest that further research should take into account the potential conflicts in safety aims: are concerns over appearance so significant to justify a more hazardous process? Could a conscious choice to minimize hazardous processing be beneficial to the acceptance of the product's appearance?[10] Finally, while there are good reasons to expect that *BC* is a truly biodegradable material, we caution over a potential blind spot: An emphasis on biodegradability may temporarily divert attention from long-term or accumulated effects of *BC* in the environment or in future circular economy loops.

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[7] Due to the timing and nature of our collaboration, this study was not meant to affect the proceedings of the *BC* consortium in any way. Thus, this section is only meant to provide the *BC* partners with an opportunity for reflection.

[8] In the course of the *BC* project, data from an LCA study suggested that one of the additives in use should be replaced by a fossil-based alternative of better environmental performance. This proposal caused some internal conflicts in the consortium, with some partners being uncomfortable with switching to a fossil-based alternative. We believe that a SbD frame could provide guidance in such circumstances and/or could motivate a different set of alternatives for consideration to begin with.

[9] Consider as an example a parallel study into potential applications of *BC* conducted by an affiliated group of students. While our interviewees evaluate applications based on safety parameters (e.g. degree of contact), this parallel study was solely organized around the material properties of *BC*.

[10] Results from two focus groups indicate that aesthetics matter for applications in which the material is visible. At the same time, it was commented that aesthetic interventions such as a paint should not negatively affect the biodegradability of the product.

7.1.2 Look for happy coincidences

In addition to systematizing ongoing safety efforts, a SbD lens may help identify additional opportunities for action. Consider as an example the *sanitation step* during the extraction of *BP*. An existing step in the extraction process was fine-tuned to improve the safety of *BP* and, subsequently, of *BC*. The sheer availability of such a step may have been a **happy coincidence** as the *BP* extraction protocol was motivated by prior work on comparable compounds. Yet, this extraction process afforded an adaptation that resulted in considerable safety benefits. A SbD lens could help identify more of these happy coincidences. We encourage the developers of *BC* to revisit parts of their production process that may afford tweaking in favor of safety.

Admittedly, tweaking and fine-tuning may contradict the tenets of SbD which would suggest designing for safety *upfront*. Nonetheless, we acknowledge that design decisions may not be always available to actors, that actors may prefer to achieve results with the least amount of redesign and that new investigations tend to focus on achieving a minimum viable product first. These are very realistic challenges for SbD and may imply that safety (e.g. as maximized via process design) is still seen as an optimization by those engaged in applied research. If so, SbD is likely to require a more radical shift in mentality. In the meantime, re-evaluating protocols through a SbD lens may enable us to intervene at a moment after performance is proven but before production is concretized.

7.1.3 Be clear about responsibility allocation

Our SbD investigation may have not revealed new risks but have certainly drawn attention to the uncertainties inherent in the *BC* system. As a useful next step, we recommend a systematic analysis on the ways these uncertainties are handled internally. Within the *BC* consortium, roles are clearly designated, with partners having concrete expectations about their own role and the role of others. Still, responsibilities for dealing with uncertainties may be less clear than responsibilities for technical tasks.

Table 5 proposes a first mapping of uncertainties to responsible actors. We hope that such an instrument can be used internally to confirm and agree on the proposed responsibility allocation, to check that the corresponding actors have the capacity to do what they are tasked to and to clarify the sphere of influence of each actor. Here, “responsibility” refers to a forward-looking notion of responsibility (Van de Poel and Sand, 2018), i.e. one that implies proactive actors who take actions in order to improve the state of affairs (or, in this case, to act upon the corresponding uncertainty). Responsibility allocation in terms of accountability or liability is not part of our mapping but should certainly be addressed internally.

*Table 5 Responsibility allocation per identified uncertainty. This overview includes only uncertainties of direct relevance to SbD, i.e. uncertainties over the impacts of BC or uncertainties that affect the consortium’s capacity to design for safety. Responses to uncertainty based on Smithson, M., & Bammer, G. (2012). BP: biopolymer; BC: biocomposite. Internal: partners of the BC consortium; boundary: partners participating in both the BC and the BP consortia; external: partners of the BP consortium (i.e. external to the BC consortium). *: applies to BP of municipal origin only.*

Uncertainty	Response	Short Explanation	Main Actor Responsible	Actor is
BP				
Risk assessment (RA)*	REDUCE	Data collection is ongoing	*BP* consortium	External
Environmental RA*	REDUCE	Data collection is ongoing	*BP* consortium	External
RA framework	REDUCE	A list of relevant contaminants for *BP* is being drafted	*BP* consortium	External
BP (composition)	REDUCE; TOLERATE	Analytical studies are ongoing; *BP* tolerated as a variable feedstock	Knowledge institution; Post-Processor	Boundary

BP (production)	TOLERATE	*BP* not likely to be modified *a priori*	*BP* consortium	External
BC				
Risk assessment (RA)	BANISH	Out of scope/ bound to *BP*	-	-
Environmental RA	BANISH	Out of scope/ bound to *BP*	-	-
RA framework	[non conclusive]	Unsatisfactory situation that should be somehow tackled	Government	External
Wastewater	TOLERATE	SbD action: Choice of applications	Engineer/Designer	Internal

7.2 What can SbD learn from the *BC* case study?

The *BC* case study has provided an inside look into the realities and practicalities of innovation at a midway stage of technology development, when both opportunities and constraints abound. Our findings challenge the stereotypical view of SbD as a practice of making informed, safety-driven choices that lead to innovations with safer properties. Rather, they point to a complex network of interdependencies across actors and to a range of uncertainties that further impede action. In response, the *BC* designers devise solutions that, in times, tolerate uncertainty and resist the illusion of control. Then, which vision of SbD would emerge if we were to formalize our lessons learned?

7.2.1 Safety is contextual and design is a verb

The *BC* developers operationalized SbD into a number of technical actions that should affect the properties (and, consequently, the safety) of their final products. At the same time, they consciously strive to maximize safety via the choice of *appropriate applications*. While not a watertight solution, their strategy invites us to rethink the scope of design actions relevant to SbD and the range of choices that a designer could be exercising. It also challenges the somewhat unfortunate obsession of SbD with maximizing safety at the material level. It reminds us that safety is not exclusively a material property (to be maximized via technical choices in the lab or workshop) but a contextual one (to be maximized *in context*). Finally, we repeat here that this shift to the design of applications is a pragmatic response to the uncertainties and constraints that the developers face. In situations where uncertainties and constraints abound, maximizing safety *in context* may be a more realistic strategy for SbD and one that is less susceptible to illusions of control.

To a lesser extent, responses suggest that SbD efforts may need to extend over time and beyond the development of a product. Typical engineering tasks such as *monitoring* and *prototyping* were overly proposed as solutions to tackle the uncertainties over the life expectancy and long-term effects of novel materials. Thus, our interviewees conceptualized SbD as a design *act* (i.e. designing iteratively) rather than as a design *product*. Iterative and stepwise implementations of SbD do exist but tend to focus on early stages of R&D; in this case, however, SbD actions and responsibilities extend beyond the development of a product. Consider as an example the suggestion that innovators continue to monitor the performance and safety of their products after launch or that the deployment of low-risk products is used to collect data on safety. In circumstances where uncertainties abound, SbD implementations emphasizing iterative learning over time may be inevitable. Nevertheless, such implementations raise additional concerns over the capacity of actors operating under constraints. Iterative learning would require enough flexibility for the lessons learned to be fed back into the value chain, which is not always guaranteed.

7.2.2 Anticipating uncertainties

Our analysis indicates that different types of uncertainties may require qualitatively different actions by different actors. For example, variability uncertainties may be best tolerated than reduced while resolving epistemic uncertainties may be beyond the scope and capacity of the engineers working in the workshop. SbD efforts could thus benefit from an anticipatory process that strives to identify not only foreseeable risks but also safety-related uncertainties. To this end, the metaphors of black boxes and open systems, while rudimentary, may help identify components of the system that are unaccounted for (black box) or are variable, uncontrollable and unpredictable by nature (open systems).

More importantly, our strong interest in uncertainties recast SbD as a problem of responsibility allocation, as opposed to a purely technical one. Different responsibilities distributed across different actors also remind us that the practice of SbD is a collective effort that is not confined to the lab or the workshop. Some SbD actions may require organizational support while others may demand action or coordination across the entire value chain. Eventually, we come to the realization that several of the questions that emerged during this study are common in organizational theory and practice. How do organizations deal with uncertainty? And how do they coordinate knowledge, actions and responsibilities across actors? Literature on decision making under uncertainty could also provide additional guidance, e.g. by providing practical heuristics, when rethinking SbD as a practice of coping with various sources and types of uncertainties.

7.2.3 Introducing SbD in new domains of practice

Introducing a SbD approach to a new domain of practice comes with its own challenges. To our experience, the need to explain SbD with concrete examples comes with the risk of propagating assumptions made by different fields of practice. Next, those advocating a SbD approach will need to clarify the conceptual and practical correspondences between SbD and existing safety practices. Our interviews suggest that practitioners easily identify with the aims and expected benefits of SbD but may have difficulties detecting the added value of SbD over existing safety practices. This skepticism is often accompanied by concerns over excessive or too restrictive regulation as a consequence of SbD.

In addition to explicating the added value of SbD, we note another suggestion on how to make SbD relevant and attractive. Several of our interviewees were positive about the **scientific challenge** that safety-related requirements introduced to their practice. Consider as an example the SbD action *choice of additives*. Interviewees remark that the consortium's implicit decision to work with natural additives provided a welcome scientific challenge. They further explain that conventional but less benign substances would have simplified their investigation and they positively comment on the scientific, technical, and intellectual challenge of working with non-obvious ingredients. This positive disposition was observed not only in the case of additives but also in the case of the *BC* concept as a whole, with two interviewees being positively surprised that a biocomposite was accomplished from the given ingredients.

Introducing SbD as an innovation opportunity was thought to have a similarly positive connotation for engineers but attracted little attention. This may be due to the consortium's prior emphasis on biobased alternatives and their increased concerns over the public and market acceptance of recovered materials.

8 Conclusion: SbD and the circular economy

This study investigated the applicability of SbD to the development of a novel biocomposite produced from recovered ingredients. To this end, we mapped the risks, concerns and uncertainties associated with this product and co-created a range of SbD actions that could potentially increase its safety. While informative, this remains a single case study with its particular innovation ecosystem and cannot represent all innovation efforts in the field of circular materials. Nevertheless, the *BC* case study underscored factors of importance that are shared by most innovations in the field of resource recovery, namely the impact of wastewater (and waste in general) as a source of uncertainty and the influence of established, multi-actor value chains.

We have identified wastewater (and waste in general) as a significant source of variability uncertainty. Our analysis suggests that, typically, waste streams are unstable, difficult to analyze exhaustively and open to inputs from their environment. This open-endedness of waste systems is here to stay, at least in the near future and with the existing infrastructures for waste and wastewater collection. Then, how should practitioners who wish to exercise SbD respond to the uncertainties inherit in waste streams? Our interviewees' tendency to resist full control and absolute safety assurances can be instructive. A "common sense" approach to application design combined with responsible monitoring emerges as one strategy for operationalizing SbD in the circular economy, where the open-endedness of waste systems is of concern. That said, our study provided only limited insights over the risks that hazardous traces pose to circularity. This could be due to our interviewees' emphasis on biodegradability (meaning that the product is not to re-enter the production cycle) or their conviction that impurities will always be part of the circular economy. It remains to be seen whether a widespread application of SbD could eliminate impurities in the future of whether impurities will remain an uncertainty designers must deal with. Either way SbD implementations may need to be more vocal about risks to circularity and safe reuse.

Designers and innovators who operate at later TRL stages and/or within partially established value chains may enjoy less freedom or flexibility than those working with radically new, emerging technologies. As discussed, SbD efforts are often affected by a compartmentalization of design choices and by increased communication and information needs. This situation hints at the limits of what can be achieved via technical design choices and calls for qualitatively different SbD actions across the value chain, i.e. actions related to communication and information transfer; coordination and allocation of task and responsibilities; and dialogue between actors. At the same time, innovators who operate at later TRL stages usually enjoy a more concrete view on applications. This could enrich our SbD efforts with available contextual knowledge and support more nuanced exchanges with relevant stakeholders (Kallergi *et al.*, 2021). Perhaps, it could also enable us to collectively generate and share SbD expertise within specific domains of practice. Standardizing communications and pooling domain knowledge into usable bits are (less typical) forms of SbD actions that are worth exploring further.

Significant to SbD in the circular economy is the realization that a safe product is not *per se* sustainable. Finding the optimal balance between the values of safety and sustainability is not only an engineering task but also a normative question for society. As such, it will require actions and deliberations that go beyond the design and assessment of a single product. Moreover, the interplay between innovation and safety and the role of regulatory bodies in this process are complicated subjects. Innovators face tangible challenges in the risk assessment of their products, especially in the long-term, with some voicing preferences for more adaptive forms of risk management. Adaptive and iterative learning practices are certainly promising but they must be accompanied by measures for the containment and management of risks, should these risks materialize. Again, a “common sense” approach to application design that takes containment into account, a dedication to monitoring and a **partnership** between practitioners and policy makers emerge as relevant SbD actions. Alternatively, it might be the case that policymakers and regulators need not only look at the future but also at the past: Evaluating established solutions with the same standards and scrutiny that novel or recovered materials are subject to would reportedly tip the scales.

All things considered, SbD in the circular economy requires us to move beyond a stereotypical understanding of SbD as a purely technical act. It asks us to incorporate theoretical ideas that accommodate the need to design under variability uncertainty and under constraints. We have suggested that, in the presence of uncertainties and constraints, SbD could be partially exercised as “common sense” application design; our study, however, generated only anecdotal data on what makes an application (context) appropriate. To this end, we point to the notion of responsible experimentation (Van de Poel, 2017) and the *conditions* that define it. Finally, we conclude that SbD efforts cannot be solely the responsibility of designers. Hence, a more expansive interpretation of SbD is needed so as to emphasize actions at the organizational level and/or across the entire value chain; in Appendix 2, we provide a revised set of SbD cards that reflects this conclusion.

Highlights

- SbD in the circular economy is challenged by uncertainties that come with waste and by constraints that come with partially established, multi-actor value chains. Both challenge SbD as a practice of making informed, safety-driven choices that lead to innovations with safer properties.
- In situations where uncertainties and constraints abound, maximizing safety *in context* may be a more realistic strategy for SbD and one that is less susceptible to illusions of control. However, this strategy cannot prevent risks related to accumulation of hazardous substances in the environment or in future circular loops.
- SbD efforts may benefit from a systematic analysis of safety-related uncertainties inherent in the system and by a clear responsibility allocation over responses to these uncertainties.
- In the presence of uncertainties and constraints, SbD efforts cannot be the sole responsibility of designers, nor can SbD be conceptualized as a purely technical act. A more expansive interpretation of SbD is needed so as to emphasize actions at the organizational level and or/across the entire value chain. Such actions may involve support for communication and information transfer; coordination and allocation of task and responsibilities; and dialogue between actors.
- SbD was not perceived (yet) by the interviewees as part of a solution to institutional uncertainties in the regulation of circular innovations. Rather, it was seen as part of an already problematic innovation landscape in need of political solutions.
- SbD communications that emphasize added value, innovation opportunities and scientific challenges of SbD may increase the appeal of SbD; such arguments, however, do not address concerns over potential negative effects of SbD on innovation.

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Appendix 1 – Stakeholder interviews

A1.1 Method

We conducted semi-structured interviews with members of the *BC* consortium in the period between December 16th, 2020 and January 19th, 2021. Due to the COVID-19 circumstances, interviews were conducted online (via Microsoft Teams) and were video recorded. Appendix 1.2 provides the participant information sheet and consent form emailed to the participants. Out of the five partners in the consortium, we invited participants from 4 organizations; 1 institute (Research institute-1) was excluded for being the problem owner of this study. In our final sample (n=8), three organizations are represented with multiple participants. The remainder partner granted us an interview but, for reasons beyond our control, we had to exclude this data from our analysis (the participant was made redundant by their organization during our data collection). In our final sample, industrial and academic stakeholders are equally represented (four academic and four industrial). With the exception of one junior researcher (PhD student), all participants are researchers or professionals of medium to high seniority, with considerable experience in the domains of polymer science, environmental engineering or biobased material production.

Interviews were semi-structured with the interviewer guiding the conversation along the expertise and interests of each participant. Each interview lasted approximate 1 hour. The exact order and formulation of questions varies per interview while some topics are indirectly covered during a different question. That said, all interviews addressed the thre mandatory parts of the interview guide:

- Background: Opening questions on the participant's role in the project; questions about the present status of BC (i.e. TRL level, most important next step/challenge)
- Safety: Questions on risk and uncertainties (main risks associated with BC, most unpredictable or uncontrollable aspects of BC); questions on risk assessment, regulation or certification.
- SbD: This part was structured as a probing exercise with participants responding to a set of SbD cards (see below)

It should be noted that some of the participants felt more knowledgeable or more driven to talk about the *BP* biopolymer than about the *BC* biocomposite. Their responses are of course relevant as *BP* is an essential part of the *BC* system. Overall, we found it useful to observe *what* each participants chose to emphasize in relation to safety and we opted for a conversation that would follow leads as they appear. Given the format of the interviews, results should be understood as purely qualitative, and no conclusions should be draw over any quantitative aspects indicated.

Early interactions with our consortium partners (i.e. during the internal update meetings attended by the researcher) suggested that SbD is an unfamiliar concept with no immediate associations to current practices. This realization motivated us to develop a visual probe to introduce the concept in an accessible manner. The probe took the form of SbD cards illustrating different interpretations of SbD. During the interview session, we used our SbD probes to walk our participants through the different perspectives and to stimulate responses about possible SbD actions. Specifically, participants were asked to choose any card they deemed relevant and to explicate examples of current or future measures that could fall under these categories. All visuals used during the interview are provided in Appendix 1.3.

The interviews were transcribed manually and were slightly edited for the sake of readability. An emphasis on readability was justified by the aims of our study. Firstly, we planned our analysis purely on information content (i.e. expert views), not on the enacted discourse or the participant's sentiment. Secondly, an accessible transcript should be easier for our participants to review, a step that we considered necessary in terms of trust. During transcription, we applied the following editing rules: Pauses and various audible reactions (e.g. laughs) were not indicated while we removed repetitive interjections (subsequent uh-s, yeah-s, etc.), repetitions of the same word ("it it it"), and too obvious false starts. The transcripts were further fully de-identified by removing both references to the participant's information and direct references to the consortium. When applicable, personal or sensitive information related to the circumstances of the interview was removed. Anonymized transcripts were submitted to participants for review and no changes were requested.

To assist our analysis and interpretation, we wrote summaries of each interview soon after each session and prior to the coding process. This step provided us with a first sense of the topics prioritized by each participant. Once all interviews were transcribed and anonymized, we proceeded with open coding. Coding was done inductively, with codes emerging for the participants' quotes, with only few codes dictated by our subject, namely those corresponding to the SbD cards. Analysis was performed using the qualitative analysis software Atlas.ti.

A1.2 Participant information sheet and inform consent form

TU Delft

Participant information sheet – Stakeholder interviews

Research project title:	**Biocomposite: Safe-by-design for the circular economy**
Primary Researcher:	Dr. Amalia Kallergi (A.Kallergi@tudleft.nl)
Supervisor:	Dr. Lotte Asveld (L.Asveld@tudelft.nl)
Last edited on:	16 November 2020

You are being invited to participate in a research project. Before you decide to take part in this study it is important for you to understand why the research is being done and what participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. You can contact us if there is anything that is not clear or if you would like more information. Take time to decide whether or not you wish to take part.

Thank you for reading this.

Purpose of this study

Safe-by-design (SbD) is a risk management approach that emphasizes risk minimization via appropriate design choices at early stages of technology development. In this research project, we examine how SbD may be applied to the development of a novel bio-composite material [redacted] that is produced from resources recovered from waste and is intended for use in the construction sector. [redacted] is produced from recovered toilet paper fibres and a novel bio-polymer [redacted] extracted during wastewater treatment.

This study will collect the views and perspectives of a broad range of stakeholders in order to 1) anticipate risks, uncertainties and societal concerns regarding [redacted] and 2) reflect on the applicability of SbD in the context of resource recovery and to innovations motivated by the principle of circularity. To this end, we want to learn from your views as experts and to hear about your experiences as professionals active in this field. Any views expressed will be considered your own, will be treated with confidentiality and will *not* be understood as reflecting your institute's official position.

What will the study involve?

You are being invited to a semi-structured interview. The researcher has prepared a list of topics that would like to discuss with you but may ask you additional questions as the conversation unfolds. In compliance with the RIVM guidelines, the interview will be conducted online using the Microsoft Teams platform.

Your interview will be video-recorded: this recording will allow the researcher to produce an accurate interview transcript for analysis. The recorded video will be used solely for transcription and will be deleted immediately afterwards. The transcript of your interview will be assigned a code and de-identified, will be stored in a secure network drive during the project lifetime and, given your permission, will be preserved in a data repository with restricted access.

Why am I asked to take part?

You have been chosen for this research because your expertise was identified as relevant to the development of a material such as [redacted]

Do I have to take part?

No, it is up to you to decide whether or not to take part. Participation is voluntarily and your decision will not be disclosed to anyone, now or in the future.

What will happen if I take part?

If you decide to participate, the researcher will arrange an online session with you. The researcher will also ask you to sign a consent form; this form must be submitted by email the latest 1 day prior to the interview.

At the start of the online session, we will check again whether you have any questions and whether you want to participate; joining the online session does not oblige you to proceed with the interview. If you decide to proceed, the researcher will ask you to orally repeat your consent to start the video recording. The interview will proceed with a few background questions followed by open-ended questions on the topics of safety, technology development and risk management. Remember that you can refuse to answer questions and can stop at any moment without giving a reason.

The online interview is expected to last approximately 1 hour. Soon after this session, the researcher will contact you again via email and ask you to review the transcript of your interview. You can request any part of this transcript to be amended or erased.

Are there possible disadvantages and/or risks in taking part?

There are no foreseeable risks or discomforts for those participating in the project.

Benefits

There are no direct benefits for those participating in the project.

Reimbursements

There are no reimbursements for those participating in the project.

Confidentiality

Your participation to this project will be kept strictly confidential and all data will be treated and analysed anonymously. Your interview transcript will be will be given an interview code and will be edited so that any direct or indirect identifiers are removed (de-identified).

This research will record personal data about your affiliation and function. This data will be stored in a secure network drive (preserved for 2 years after the end of the project) and will not be shared with anyone outside the research team. We will use this data to assign you a profile, expressed in generic categories. This profile will be used to aggregate results and to compare views of different stakeholder groups. Any communications about the results of this study will only refer to your assigned profile. You will not be identified in any publication from this study.

Collected data will not be used or made available for purposes other than this research project. No person other than the primary researcher will have access to the original video recordings, which will be destroyed immediately after transcription. You can request and review any personal data stored in relation to this project and you can ask for this data to be changed or erased at any moment after your participation.

What will happen to the results of the research project?

The results of this research will be used to produce an internal report for the funder of this project. You can request a copy of this report from the primary researcher (A.Kallergi@tudelft.nl). The results of this research may also be communicated in scientific publications. Given your permission, anonymized quotes may be used in these research outputs. Given your permission, de-identified interview transcripts will be preserved in a data repository with restricted access and may be shared with other researchers so that scientific findings can be validated.

Right to Refuse or Withdraw

You can refuse to answer questions and you can stop at any moment without giving a reason; the remainder of your responses will be processed unless you also choose to withdraw your consent. You can withdraw your consent verbally during your interview or by emailing the primary researcher (A.Kallergi@tudelft.nl). We can process this request for as long as it is reasonable to do so (i.e. prior to communication of results).

Who is organising and funding this research?

This research project is organised is by Delft University of Technology and funded by the Ministry of Infrastructure and Water Management.

Ethical review of the study

This research project has been reviewed and approved by the Human Research Ethics Committee of TU Delft.

Who to Contact

For inquiries about this research project, involved procedures and the processing, storing or and sharing of data and research results, you can contact the primary researcher: Dr. Amalia

Kallergi (A.Kallergi@tudelft.nl). For inquires made after the project lifetime (i.e. September 2021), you can contact Dr. Lotte Asveld (L.Asveld@tudelft.nl). For inquiries about your personal data, you can contact the privacy team (privacy@tudelft.nl). Should you have felt uncomfortable in any stage of your participation or should you have a complaint about this research project, please contact Dr. Lotte Asveld (L.Asveld@tudelft.nl)

TUDelft

Informed Consent Form
"Biocomposite: Safe-by-design for the circular economy"
Stakeholder interviews

Please tick the appropriate boxes	**Yes**	**No**
Taking part in the study		
I have read and understood the study information dated 16/11/2020. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	O	O
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	O	O
I understand that taking part in the study involves a video-recorded interview conducted online.	O	O
Use of the information in the study		
I understand that information I provide will be used for writing an internal report and that results may be communicated in scientific publications.	O	O
I understand that personal information collected about me that can identify me, such as my affiliation and function, will not be shared beyond the study team.	O	O
I agree that my information can be quoted in research outputs.	O	O
Future use and reuse of the information by others		
I give permission for a de-identified transcript of my interview to be archived in the DANS Easy repository under restricted access so that scientific findings can be validated.	O	O

Signatures

____________________ ____________________ ________

Name of participant [printed] Signature Date

I have provided the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

____________________ ____________________ ________

Researcher name [printed] Signature Date

Study contact details for further information: Dr A. Kallergi (A.Kallergi@tudelft.nl)

A1.3 Visual aids

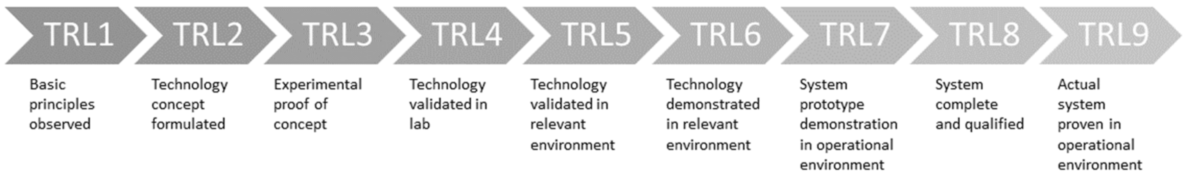
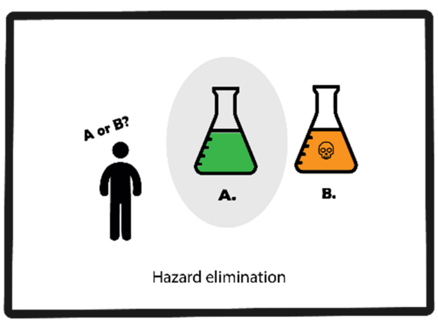
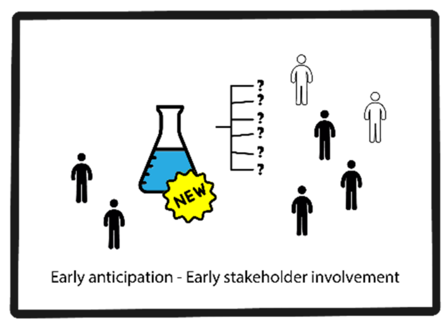
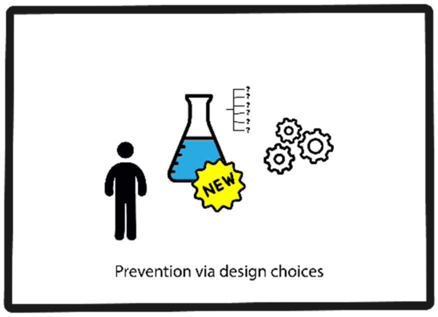


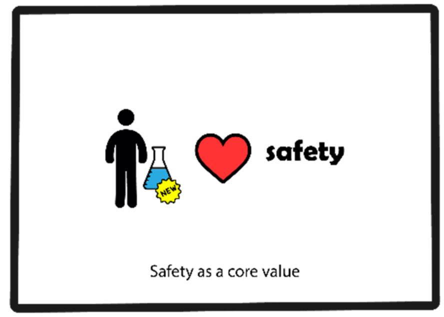
Figure 1 TRL scale

Table A-1 SbD cards: A visual probe illustrating different interpretations of the concept of SbD. The cards are not categorically exclusive and only aim to highlight possible interpretations of SbD ('lenses'). The illustrations were used to introduce SbD to the interviewees and to probe concrete responses per perspective.

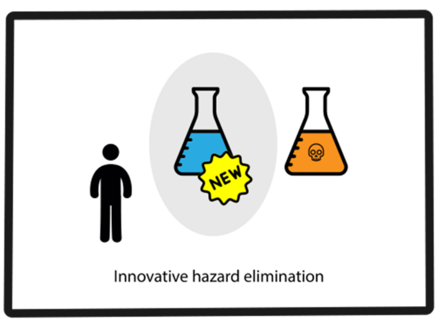
	
SbD as Inherent safety: Inherent safety, one of the predecessors of SbD, suggests that the designer of an experiment, product or process should always prioritize the most benign design option. This approach, however, is only possible when historical data on safety are available.	**SbD as Early action**: SbD suggests that scientists and innovators ask the "what may go wrong?" question early on in the development process and that they do so in an inclusive manner, i.e. by taking stakeholder perspectives early on into account. SbD as such assumes that (collectively) anticipating risks at early stages of research and development enables us to deal with them better.



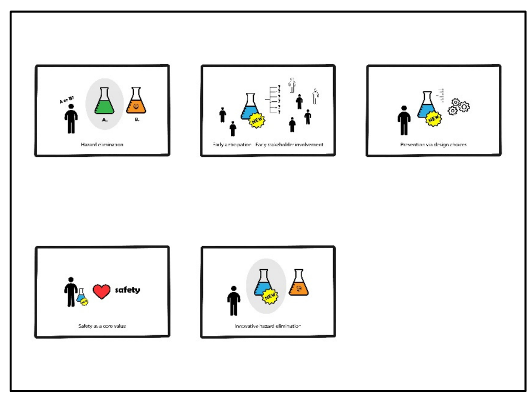
SbD as Design: SbD suggests that safety can be maximized upfront by means of appropriate design choices. In the case of emerging technologies, such choices should be made already at the conception of an innovation: A material or organism is explicitly designed with safety as a requirement, using measures and tools that are specific to the discipline. SbD as such assumes that safety is a property internal to the technological product.



SbD as Value proposition: SbD suggests that safety can be maximized if acknowledged as a core value. This is a normative position with implications for what we consider as sound and responsible science and innovation. The value of safety underlies all understandings of SbD; however, SbD as such implies that positive change is predominantly a matter of awareness and less a matter of a standardized methodology.



SbD as Innovation opportunity: In the context of material sciences, SbD can also be understood as an innovation opportunity. The aims of SbD (eliminate hazards; maximize safety) could be achieved by designing new and safer alternatives to known hazards. To design for safety, thus, becomes to innovate intentionally and with safety as the main objective.



Summary page SbD cards

A1.4 Known risks as identified by interviewees

Table A-2 Risks associated with BP and BC as identified by interviewees. NB: A mention of a risk does not imply that the risk is high, only that it is deemed relevant. A: Academic stakeholder; I: industrial stakeholder.

	Participants	**Short description**
Contamination		
Contaminants – Pathogens	A1, A2, A3, I2, I3, I4	Municipal wastewater contains pathogens that may end up in the final product (*BP*)
Contaminants – Heavy metals	A3, A4, I2, I3, I4	Municipal wastewater contains heavy metals that may end up in the final product (*BP, BC*)
Contaminants – Other	A1, A3, I2, I4	Municipal wastewater contains other contaminants (e.g. pharmaceuticals, DNA fragments, etc.) that may end up in the final product (*BP, BC*)
Microbial growth during storage	A2, A4, I3	*BP* spoils during storage; harmful microorganisms might be present
Unsafe operation		
Malfunction; unreliable operation	-	[not raised; scope from extraction onwards]
Fumes during production	I1	Fumes are released during *BC* production; may or may not be harmful
Toxic derivatives during reaction	A4	Toxic substances may be formed during *BC* production
pH crude biopolymer	A2	*BP* is provided in alkaline or acidic versions
Feasibility		
Strength	I1	*BC* may not be strong enough for target application
Smell	A3, A4, I1, I4	*BP*, *BC* have an unpleasant smell
Appearance	A3, A4	*BP*, *BC* have an unattractive color
Degradation		
Due to time	A4, I1	The mechanical properties of *BC* degrade over time
Due to microbial or insect activity	-	[not raised]
Due to water absorption	I1	The mechanical properties of *BC* degrade as *BC* absorbs water
Residues/ Emissions	I1	Residues or leached substances
Public perception		
Societal acceptance	A1, A2, A4, I1, I4	*BP*, *BC* will be negatively perceived/ not accepted
Sustainability		
Ecological	-	[cf. risks to ecosystems]
Economic	A1, A4, I2	Business risks to the innovation
Societal	-	[cf. risks to workers]

A1.5 Representative quotes uncertainties

Uncertainty source: BIOPOLYMER

[BIOPOLYMER] is unknown	"the composition of these polymers, how they look like, what they are, how the chemistry is, is unknown." (A1) "And even I think it's not only us at [OWN COMPANY], even people who work directly, for them is sometimes strange, like the behavior is not predictable and maybe even the structure is not well known, it's very different than when you work with a conventional polymer of course, you know all the properties." (I1) "Because [BIOPOLYMER], the chemical structure of [BIOPOLYMER], the physical structure is poorly understood and that limits also how far we can optimize the process if we do not fully understand what it looks like, right?" (I2)
[BIOPOLYMER] is inconsistent	"we have two sources of [BIOPOLYMER] and even I think from batch to batch they are slightly different, but this is not something very strange because biobased materials cannot be 100% consistent in their behavior. But I think we should at one point find a trend, or at least, you know, understand a little bit how this material reacts in composites, as far as composites are concerned, and maybe find some consistency because that's I think the main problem now. (I1) [in reply to the question what is the most uncontrollable or unpredictable aspect:] "I think the resin part, when we get the resin part over here and you don't know exactly what will happen" (I3) [in reply to the question what is the most uncontrollable or unpredictable aspect:] "I think the nature of the source of material, still, although it's always analyzed and we get different batches of [BIOPOLYMER] in [OWN COMPANY], I think it should be more, somehow, consistent" (I1)
[BIOPOLYMER] is a black box	"so they get the material from us and then they use it as they get it" (I2)
Information needs	"we needed more, I think this feedback, especially feedback from [PARTNER], was not that strong. Well, at least personally, I expected more from [PARTNER], the contribution, because we simply cannot play around a lot with what we get, the [BIOPOLYMER], wet [BIOPOLYMER] or powder [BIOPOLYMER] that we get from [PARTNER], that's the way it is." (I1) "When they deliver a resin to us it should be together with the safety data sheet and technical data sheet. But it's R&D." (I3)

	“so we asked them, what is in it? Are there heavy metals? Can we make products that can be touched? We smell something. What is this smell? Is it dangerous? Is it not? We are in a shared lab, so if our neighbors smell anything, they ask us, what is it? We don't know what's the smell. Is it hazardous? Can you prove it? Where's the data sheet? Where is the data safety sheet? Of course, we don't have one yet. Only a very empty one saying no, hazards: no, but it smells like hell, so there's a bit, so we need this input of course.” (I4)

Uncertainty source: Wastewater

Something weird thrown in the sewage	“It comes from wastewater so you have to always take into account that there might be something from, what is thrown through the sewer by someone ending up in the product and you never know what it is.” (A1) “So the hazards introduced are that, yeah, maybe there are some heavy metals, maybe people put paint in the sink and it is in the material. But, on the other hand, the alternative materials are the same as the paint is in the 1st place.” (I4)
You never know what is in there	“you never know, you cannot declare all the compounds which are in the material 'cause it will never be pure.” (A1) “so it's a waste stream, yeah, you don't know what people throw through the bin or through the sink.” (I4)
We cannot guarantee is risk free	“So you have to intrinsically, um, assume that there is something wrong in it, so you should not put it on applications where you don't want to have it” (A1) “there's always a small hazard that you don't know exactly what's put into the system. That's always, as I explained, it's always with the recycling, we cannot eliminate every hazard because it's inherent to the system that we cannot eliminate it all.” (I4)

Novelty and regulation

Other contaminants	“if you have your anti-sticky pans and you clean them every time in the sink. And some PFAS residue can get into a material and if we bury it for underground construction, I can imagine that things happen. But maybe it is very small, so I don't know how large is this and if it's X percent? .001%? Is this a problem or not? I don't, I don't know.” (I4)
Regulation is not there	“we also work with the same people that they have worked for at [COMPANY], that did this or are doing this end-of-waste for struvite. And basically what the government said is develop your own framework and then we tell you whether we agree or not. But they

	developed a framework of a very long list of pharmaceuticals which are reasonable to expect in struvite, but it's a very different product from [BIOPOLYMER] so we have to redo it for [BIOPOLYMER].” (I2) “I think it's still, I think it's state of the art now of research. We also have this discussion with biodegradable plastics and on the other hand we have the discussion on microplastics and to what particle size are plastics still problematic? Or about fire retardants, pigments, flowing improvement additions, etc. Lots of additives are added to plastics so it's not an easy discussion. I can imagine that on the molecule level it's not really a problem, but I can imagine that it is, so I don't know. It's a moral and ethical discussion as well. And we're, say, engineers, we can only say the particles are this and this big and they get in the environment. And other people and politics should decide whether this is a problem or not.” (I4)
Regulation is outdated/ based on conventional technologies	“on one hand the legislation is irritating because it doesn't fit for purpose. On the other hand, you have also the problem that the legislation doesn't fit, you know that it's doing a bit stupid, but you can just follow the legislation and still you know there are risks which are not under the legislation.” (A1)
Time factor risk assessment	“is also hard to prove that the risk is very small because we don't have experience with it and it's hard to, I cannot prove that this material is not hazardous for the people processing it in 25 years time. I cannot prove it because we never processed it for 25 years, we just started.” (I4) “We come on the market and that we don't know the lifetime expectancy for instance. So if we could make a bridge of biocomposite materials, we don't know, is it safe in 30 years or in 40 years? And because we don't know, it's unsafe. And because it's not safe, we will not use it. So we will still produce bridges out of concrete or steel. So there, the safety discussion is a threshold to innovate.” (I3)
Safety is a threshold for innovation	“we are a small innovative company fighting the big companies who have already a position so I can imagine that maybe aluminium companies say "you see there's a problem with this, so use aluminium, then we don't have that problem".” (I4) “the norms for safe are being set up most of the times by the existing industry. So for us, safety is a threshold for innovation. […] Because safety is so very important that people use it as some sort of fence for new materials to come onto the market and they say it's not safe what you are doing.” (I3)
Risk acceptance	“Now you see with electrical cars that, uh, it's very dangerous because the firemen don't know what to do in this high voltage systems and

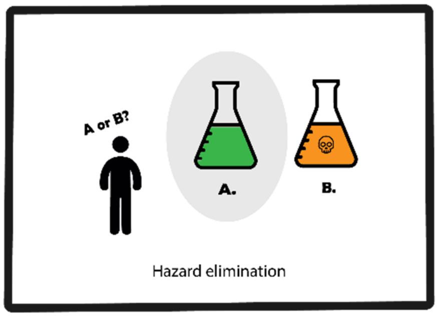
	how do we know, it's a lot of discussion about how dangerous it is. And then, I think, yeah, but look at the concept of the gas station. We would never allow, if you want to introduce a concept like that now, you wouldn't be able to do it" (I4) "So sometimes people ask me: can you prove that, well, what I said, that the people processing it will not have cancer in 25 years because of this. Of course I can't prove it. And then they say: well and then I ask them: why is this necessary? And then they say: of course, yeah, we don't want people to die of cancer. And then I say: yeah, but how did you get here to this meeting, and they say: I drove my car, I say: OK, how fast were you driving? they say: well under 20 miles an hour, I say: yeah, it would be safer for it to go 60 and still you didn't do it. So there's always a risk and it's all about assessment and I think that the way people handle it or compare it is not rational because unfamiliarity plays a not rational role" (I4)
Too much risk aversion is bad	"I think that, I mean, there's always a, and that's generally applicable, is that if you want to do something with a certain motivation to do something, for whatever good reason, then sometimes it involves taking risks and these risks are, shall we say, inevitable or basically come with the whole game here. So if you start climbing Everest, you know beforehand that you might get killed by a falling rock or an avalanche or something. Should we stop? Should we stop climbing Everest? Maybe not, so sometimes you need to be aware that some human activities do involve risks, and you shouldn't be eliminating all things worth doing by saying "well, we're going to eliminate absolutely everything", so you need to also take that into account, you need to have a good motivation why you do something, you need to be very sure that you're taking the best measures possible, but you shouldn't take it in such a way that all possible enterprises ceases to exist because you're basically doing too much risk aversion. You need to be aware of risks and you need to deal with them in an appropriate way." (A4) "If your parents who are too focused on safety, you will not let your child walk because it can fall and it can hurt itself, then it will never learn to walk. What you do is you let your child walk and it falls on the ground but it's not a big problem because it learns from it. If you're too focused I mean on diminishing or on optimizing only safety then you will do nothing anymore. So there will be no innovation." (I3)

A1.6 SbD actions proposed by interviewees

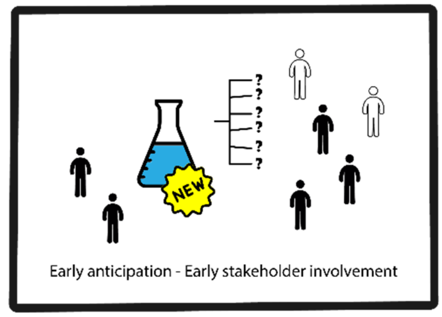
Table A-3: SbD actions generated by interviewees. Actions in square brackets [] were brainstormed in the context of SbD but are not yet implemented; actions without square brackets are already implemented and recognized by interviewees as pertinent to SbD. We also provide a rudimentary mapping of identified risks (cf. Table A-2) to corresponding SbD actions. NB: Identified risks can only capture risks specific to BC and cannot reflect the range of risks avoided; overall gains in work, product and environmental safety are indicated as other.

SbD action	Short description	Participant	Related risks
Sanitation step extraction	We kill pathogens during the extraction process	A1, A3, I2	Contaminants – Pathogens
Choice of additives	We only use natural, non-toxic additives	A3, A4, I1, I2	Residues/ Emissions; *Other*
Appropriate applications	We choose applications that minimize the risks	A1, I1, I4	Contaminants – Other; Contaminants – Heavy Metals; Strength; Smell; Appearance; Degradation (all); Societal acceptance
[Monitor]	We should monitor the material over time	I1, I3	Degradation (all); Residues/ Emissions
[Prototype]	We should build incremental prototypes	I3	Degradation (all)
Industrial instead of municipal	We (could) use *BP* from industrial wastewater	A1, I4	Contaminants (all)
[Dedicated step for heavy metal rich wastewater]	In case of a wastewater rich in heavy metals, we could introduce a dedicated step for their removal	A3	Contaminants – Heavy Metals
Remove impurities at recycling	We should remove impurities during recycling	I2	Contaminants (all)
[Low storage time]	We could minimize the storage time of *BP*	A2, A3	Microbial growth during storage; Smell
High temperature production process	High temperatures during the production process should kill pathogens	I3	Contaminants – Pathogens; Microbial growth during storage
[Reinforce in a sandwich panel]	We could reinforce the material by placing it in-between two layers of stronger material	I1	Strength
[Education]	We could introduce SbD in the curriculum	A4	*Other*
Good team	A good team can make balanced risk decisions	I3	*Other*
[Inventory of risks]	We should have an inventory of relevant risks	I4	*Other*
[Inventory of solutions]	We should have an inventory of existing solutions	I4	*Other*
Safety sheet	We should have a safety sheet	I1	Fumes during production; *Other*

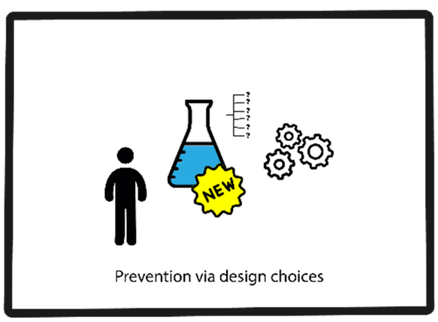
Appendix 2 – Revised SbD cards



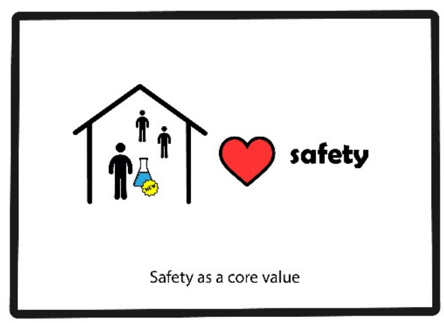
SbD as Inherent safety: Inherent safety, one of the predecessors of SbD, suggests that the designer of an experiment, product or process should always prioritize the most benign design option. This approach, however, is only possible when historical data on safety are available.



SbD as Early action: SbD suggests that scientists and innovators ask the "what may go wrong?" question early on in the development process and that they do so in an inclusive manner, i.e. by taking stakeholder perspectives early on into account. SbD as such assumes that (collectively) anticipating risks and uncertainties at early stages of research and development enables us to deal with them better.



SbD as Design: SbD suggests that safety can be maximized upfront by means of appropriate design choices. In the case of emerging technologies, such choices should be made already at the conception of an innovation: A material or organism is explicitly designed with safety as a requirement, using measures and tools that are specific to the discipline. SbD as such typically assumes that safety is a property internal to the technological product.



SbD as Value proposition: SbD suggests that safety can be maximized if acknowledged as a core value. This is a normative position with implications for what we consider as sound and responsible science and innovation. The value of safety underlies all understandings of SbD; however, SbD as such implies that positive change is a matter of awareness, commitment and support across the entire organization.

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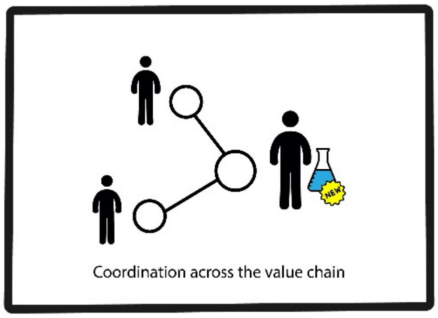
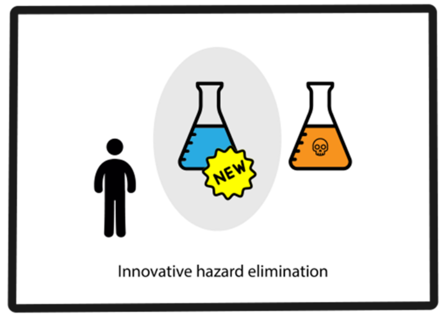
<td>

SbD across the Value chain: SbD suggest that designing for safety requires the coordination of different actors across a value chain. This means actions that support communication, information transfer, dialogue, and responsibility allocation over tasks and uncertainties. SbD as such assumes that maximizing safety is an organizational problem rather than a design one.</td>
<td>

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