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Building a new generation of SSbD agents

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This essay describes the competencies that chemical engineers need to ‘do chemistry differently’: they need to be able to question their own assumptions, collaborate with other disciplines and integrate safety and environmental performance in the design of chemicals and chemical products.

Chemistry has brought us many innovations and useful products that have become indispensable to our daily lives. However, how we have deployed chemistry and chemical products in our lives and global economy has caused the crossing of the planetary boundary for new chemical compounds years ago, resulting in many environmental problems and challenges. For instance, pollution by plastics, PFAS and chemical pesticides have disrupted ecosystems. We have become aware that to solve and prevent such problems from happening again in the future, we must change the way we do chemistry. Such change presents an opportunity to reshape the way we innovate to arrive at responsible, safe, and sustainable designs of chemical products and processes—but it also comes with challenges. Doing chemistry differently requires chemical engineers with different competencies and skills. Ideally, chemical engineers should apply a holistic perspective when designing new chemical compounds and products, which comes down to three main skills.

They need to be able to:
1. question their own assumptions and knowledge barriers on what is safe, what is sustainable, what (adverse) effects we could foresee, and how we can anticipate these;
2. work together with people from other disciplines, as all are needed to design for safety and sustainability;
3. integrate broader considerations like safety and environmental performance in addition to ‘functionality’ of the chemical.

In this essay, I present a way to build a new generation of chemical engineers who can take on the challenge of making chemical innovation more safe and sustainable through integrating Safe and Sustainable by Design (SSbD) principles in education. This includes acquiring ethical and philosophical skills for responsible decision-making, engaging in transdisciplinary work, and adopting a design approach that allows for inclusion of multiple criteria.

The concept

SSbD is an approach comprising engineering and procedural principles to arrive at safe and sustainable innovations in the chemical industry. The concept provides guidelines for developing materials and implementing process conditions with fewer hazards or lower risks. Innovations in development come by necessity with a lack of knowledge and thus uncertainties. To fill in such knowledge gaps responsibly, the SSbD approach iteratively integrates knowledge on the adverse effects of a material, product, or process into the design process. This way, a range of measures can be designed and implemented with the aim of anticipating potential issues (proactive or preventive measures) and acting accordingly to newly obtained knowledge (reactive measures) once an innovation matures. A holistic perspective must be applied as many issues occur due to (external) effects once introduced in society and nature.

While the goal of SSbD is to eradicate (potential) risks and hazards and to prevent issues from arising in the first place, history has shown us that we can remain unaware of the adverse effects of chemical products until damage has been done. As our world is already filled with such chemical compounds, e.g. CFCs, asbestos and glyphosate, SSbD principles should also be considered for degradation, recycling, and external environmental effects. Therefore, a chemical product's value chain should be considered to the largest extent possible. By consulting a range of stakeholders in an innovation's early development stage, one can gain insights into potential issues related to safety and sustainability, and use this knowledge to make design choices accordingly, to eventually arrive at a collective, safe, and sustainable design. As these aspects depend on many factors, the involved stakeholders' expertise should reflect this, for instance, ecologists, (bio)ethicists, philosophers, policymakers, toxicologists, and representatives of industry and nature conservation organisations. This way, potential issues or risks may become known early on in the process, and different design choices can be made to circumvent the potential issue, or preventive measures can be developed and implemented.

> *This new generation chemical engineers needs to be able to make decisions responsibly and assessing the importance of missing information.*

However, some adverse consequences can be difficult to predict and imitate in laboratory settings or through simulations, as they occur through external effects in nature. For example, an additive that makes car tyres' rubber longer lasting turned out to react with ozone, forming a new compound highly toxic to a specific species of salmon[30]. This illustrates that the innovation process is never finished, and we should allow for iterations; we need to be able to learn from our mistakes or matters initially overlooked. Policymakers and regulators are also crucial to such adaptations and refinements.

The challenge

Designing for safety and sustainability comes with challenges and uncertainties; when innovations are still in their early design phase, how can we determine a threshold to decide on what is safe or sustainable 'enough'? To deal with such questions, our chemistry education should be set up differently. The transition to SSbD can only be made with more broadly trained chemists with a different mindset, one that urges to consider safety and sustainability in the early design stages of chemical substances and processes, encourages working with other disciplines and acknowledges the limits of one's own expertise.

But how to arrive at engineers that have these specific capabilities? What exactly should become embedded in education to develop this mindset? Engineers need to be able to apply a holistic perspective to new chemical innovations. Besides knowledge of technical matters, feasibility, and economic motives, they must also gain insight into product-, process- and environmental safety, sustainability, and other potential issues. For this, students must acquire interdisciplinary skills and learn to think from a value chain perspective. Stakeholder engagement and co-creation are therefore essential. 'Future-proof' chemical engineers must be able to recognise their own boundaries regarding knowledge and expertise and learn to identify what knowledge and information is missing and in what disciplines or domains that can be found. Thereby, they should have the skills to decide responsibly on where to draw the line for identifying and assessing potential issues arising—we cannot consider everything that can happen to chemicals during their entire life cycle.

Value chains and system boundaries

Arriving at safe and sustainable chemical products and processes demonstrates the importance of considering the entire value chain, but where does it end? There comes a moment when decisions need to be made for a developing technology to proceed to the next level in development. In addition, while sustainability assessments and life cycle assessments (LCA) provide valuable information on the environmental impact of a product or process, their predictive value depends on the system boundaries. These determine the inputs, outputs and impacts considered in such an assessment. This raises the question of where to draw the line regarding such a system boundary and how reliable such assessments are when many aspects are still uncertain. For instance, we can develop an alternative to the chemical pesticide glyphosate, but what range of potential effects do we need to consider?

Does our ecosystem end with application in soils, or should we also consider the external effects of compounds and organisms in groundwater or wastewater treatment systems?

While newly developed chemicals are only allowed on the market with proper testing, only so much can be imitated in laboratory settings and simulations. In addition, such tests are generally designed to check for direct effects of exposure and the expected issues—it is hard to grasp long-term, indirect effects. Therefore, implementing an SSbD mindset in chemical engineering requires a multi-actor perspective. Besides toxicologists and experts in LCAs one should consult ecologists, (bio)ethicists, prospective users, policymakers, safety scientists, and society representatives to arrive at a mutually shared understanding and assessment of safety and sustainability. Together, knowledge gaps can be indicated through multiple perspectives, and, for instance, additional risk research can be set up. This should be an iterative process in which newly obtained knowledge is fed back into the design process as the chemical innovation matures. Design choices can be (re)considered accordingly. This will also ensure that designs become resilient and suffer less from lock-ins, for instance by preventing the dependence of industries on a particular hazardous chemical compound or product. We now know that PFAS come with severe health risks, but due to their favourable characteristics, they are also widely used in materials and technologies needed for the energy transition. Such dilemmas are what the chemical industry, and thus the new generation of chemical engineers, have to try to prevent from happening in the future. This calls for a responsibility pertaining to the chemical industry and illustrates the importance of sharing newly obtained knowledge and data. PFAS being the most descriptive, there are many examples of companies that decided to follow through with their chemical product, despite having new information on detrimental effects. Sharing this information, thus enabling early reaction, could prevent dilemmas and lock-ins.

In practice, this would mean that the new generation of chemical engineers should be able to identify what knowledge they are missing and where to get it from. They should be able to contact, involve, and work with actors with different expertise, see the added value of such additional insights, and discuss and co-create. Students should acquire these skills in their education. They should learn chemistry, including methods to assess notions of safety and sustainability, such as risk assessments and LCAs, but should also be involved in interdisciplinary projects. This way, they can gain insights into the boundaries of their knowledge, and develop the needed skills to tackle important questions like what safe and sustainable enough is, and where a product's value chain ends.

Ethics and project-based learning

I have argued why SSbD is needed to train a new generation of chemical engineers and what aspects of SSbD should be considered. This new generation needs to be able to make decisions responsibly—determining what safe or sustainable enough is, and assessing the importance of missing information. Such questions place great responsibility on them, so they should also be equipped with responsible decision-making tools. Ethics of technology are of utmost importance in teaching students how to deal with dilemmas, what weight to assign to findings on potential issues and the respective trade-offs for responsible decision-making.

Many engineering programs include engineering ethics, which includes principles and guidelines that engineers should follow to make responsible decisions. However, these principles and theoretical guidelines can remain rather abstract for chemical engineering students. Students need to learn by doing—only then abstract notions like 'responsibility' can become tangible. In project assignments or project-based learning, students can learn from actual cases in which a clear dilemma is set.

Applied ethics and SSbD principles can be integrated into education by letting students work on (historical) cases on which much information is available. That way, dilemmas are presented clearly, and the potential consequences of any decision or action for this case can be overseen. These dilemmas need to come from practice, as they must be able to empathise and realise that such dilemmas can also arise later in their career. For instance, students must recognise that safer or more sustainable alternatives often lead to value conflicts; they could be more expensive and require different process conditions such as a higher temperature or lower pH. In such choices, there is not one correct answer, but a responsible decision depends on the argumentation provided and, thus, the weight assigned to a specific value. For instance, sustainability may be favoured over a chemical's reaction rate. At Delft University of Technology, we aim to integrate ethics and SSbD principles in courses in several Bachelor's (BSc) and Master's (MSc) programs. For instance, in a BSc chemical engineering course on sustainable process technologies, we let students work on cases in which they are given two options for adjusted process conditions: an established method that is efficient and predictable and one that aims to increase safety and sustainability but comes with uncertainties in terms of effects. By determining and analysing various factors that play a part in responsible decision-making (e.g. efficiency, costs, effectiveness, sustainability, safety and security), students have to recommend which adjustment can be considered the most responsible choice from their perspective. Therefore, students must indicate knowledge gaps and provide recommendations on how these could be overcome, for instance, through SSbD principles. Again, there is no right or wrong answer, but it helps students develop a broader perspective to a case rather than just a technical one. Most importantly, they face the boundaries of their own knowledge and expertise, which illustrates the importance of working together with others.

> *The stakes are high; together, we can make safe and sustainable chemistry work.*

Following this, creating the SSbD mindset through project-based learning is ideally suited for MSc projects or thesis research. In such projects, students consider early-stage technologies or applications. This means the system boundaries and outcomes are uncertain and potential value conflicts are as yet unknown. It is up to the students to engage with other actors to gain insights into missing knowledge and learn how to co-create. Such interdisciplinary work reflects the complexity of innovating responsibly and clarifies the need for holistic perspectives to work towards safe and sustainable designs in chemistry.

Final thoughts on SSbD

A study program that integrates an SSbD mindset is itself an iterative process in which we constantly learn, adjust, implement changes, and repeat the cycle all over again—a program that covers exactly all SSbD elements. This is a gradual process. Some students need time to let the idea sink in of becoming a chemical engineer with a broader skillset compared to their predecessors, which may even cause some resistance. And that is fine. Every lecture, project, or thesis on designing for safety and sustainability is one step in the right direction.

Over the past years, SSbD has gained momentum as part of the EU Green Deal to make Europe’s chemical industry safer, more sustainable, and even circular. Many industry partners are collaborating with the Joint Research Center to establish clear SSbD guidelines for which EU funding has become available. However, to adopt SSbD in this industry, they need people who can do this. Therefore, funding should also become available for educational institutions to develop a framework that embeds the required SSbD elements in education programs, such as applied ethics, co-creation, stakeholder engagement, and project-based learning. Member States could use this framework to initiate and monitor such developments in education and to strengthen their current educational system.

Now that SSbD is gradually becoming more implemented in industry practices, this gives rise to many new insights and knowledge on potential risks, issues and hazards. Ideally, the iterative character of an SSbD design process should become integrated with policy and regulation on SSbD and. If new knowledge arises, we should take full advantage of this to transition towards safe and sustainable chemistry.

We are never done learning. The adoption of SSbD principles continues after completion of a BSc or MSc program. We encourage institutions and organisations to host events for professionals and postgraduates[31].

The stakes are high; together, we can make safe and sustainable chemistry work.