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Sustainability of paper and paperboard as a contextual approach to applying systems thinking in chemistry education

Stephen A. Matlin[a,b] Peter G. Mahaffy,[c] Klaus Kümmerer.[d]

a. Institute of Global Health Innovation, Imperial College London, London SW7 2AZ, UK
b. International Organization for Chemical Sciences in Development, 61 rue de Bruxelles, B-5000 Namur, Belgium
c. Department of Chemistry and the King's Centre for Visualization in Science, The King's University, Edmonton, Alberta T6B 2H3, Canada
d. Institute of Sustainable & Environmental Chemistry, Leuphana University, Universitätsallee 1, Lüneburg, Germany

This talk aims to illustrate the value of systems thinking in a contextual approach to chemistry education, using the sustainability of paper and paperboard as an example. Systems thinking is an essential competency for achieving sustainability, delivering the ability to analyse, understand and interpret complex systems.

A system is a set of components working together and an important property is that systems can change over time. This capacity to be dynamic means that an overall function can be produced, which emerges from the working of the system. So, for example, the system can be an object such as a clock that tells the time; or it can be a process such as a management system. Here we see the emergence of the function from the working of the whole system. It is apparent that the overall function cannot be obtained from the isolated parts separately, so, for example, time-telling is not a property of individual cogs and springs in a clock. This aspect of systems is of particular relevance when we come to talk about sustainability because, as we shall see later in this talk, sustainability is a property of the whole system – it is not simply a property of individual elements of the system.

Five years ago, our group at IOCD published an article in which we argued that chemistry needed to undergo a major reorientation in order to make its optimal contribution to meeting global challenges – especially sustainable development – and we called this new orientation 'one-world chemistry' and emphasised that it needed to include, among other attributes, the development by chemists of competence in using cross-disciplinary approaches and in systems thinking. It is evident that building these competencies must begin with chemistry education.

One of the outcomes of our publication on one-world chemistry was that we began a collaboration with Peter Mahaffy, which resulted in an IUPAC project on Systems Thinking into Chemistry Education (STICE) which Peter and I co-chaired. As well as a special issue of the Journal of Chemical Education, the STICE project led to the development of a new tool to help in visualizing system interactions involving chemistry, which we named the Systems-Oriented Concept Map Extension (*SOCME*). I will be using this tool in this talk to illustrate how it can help to build and deepen chemistry education approaches that reinforce analytical and questioning skills. More recently, we have followed the STICE project with a new IUPAC project on Systems Thinking in Chemistry for Sustainability.

Let's look at an example using a class of products handled daily by people around the world: paper and paperboard, which are products manufactured from wood pulp using a range of chemical processing steps. The paper and paperboard industries make some very bold claims for their products. One forum representing industry users says that “Paper is one of the few truly sustainable products” and it aims to counter “the myth that paper is bad for the environment”. Another global industry-based federation concerned with some types of printing states that “Paper is one of the few products which is completely sustainable.” How do we go about constructing a SOCME that will help us to see the roles that chemistry plays, identify chemistry learning opportunities and also evaluate these industry claims?

Often, a useful place to begin is to first sketch out a flow chart that follows the material and covers the product life from beginning to end, as might be done in a circular economy or life cycle assessment approach. In this case we might start with growing trees in forests and felling them, to produce the first rough wood trunks and logs, known as roundwood. After the bark is removed, the wood is then broken into wood chips and these are heated with chemicals to produce a suspension of fibres in a chemical solution. After separation, the wood pulp fibres are layered on a surface where they will dry and become thin sheets of paper or thicker sheets of paperboard. After any special treatments or finishes are applied, these products will be consumed in a wide variety of different uses. Some used materials are collected after primary use and disposed of in many different ways. And other products, by-products and intermediates may also enter the disposal systems.

Now we can take note of where the paper and paperboard industries base their evidence for claims of a near-perfect degree of sustainability for their products. The industry emphasises particularly (i) that wood is a renewable product, ethically sourced from places that practice certified and well-regulated “sustainable forest management”; (ii) that there is very efficient recycling of reagents and energy within the wood pulp factories; and (iii) that some paper and paperboard is recycled. Each of these aspects needs to examined in detail, but we also see that there are many other stages to the life course of paper and paperboard that require looking at if we want to know about the totality of impacts on Earth and societal systems.

So, we need to take a step backward and look at the bigger picture by factoring in the systems for input of materials and energy at every stage, and examining the interactions of all stages with the physical and biological systems of the planetary environment and the societal systems through which human beings make use of and regulate paper and paperboard.With this as a guide, we can begin building a SOCME by considering the source of wood for making paper and paperboard, for which around 4 billion trees per year are felled to provide the raw material, ‘industrial roundwood’. The bark is removed, and this will later be burned as a fuel to provide the heat for the pulping process. The wood itself is cut into chips which are converted to wood pulp either by a mechanical process in which the chips are ground at high temperature with water, or in the so-called ‘kraft’ process, in which they are heated with a solution of sodium sulfide and hydroxide. These early steps in wood pulping provide opportunities to learn about combustion and the nature of oxidation reactions and about selective cleavage reactions in organic compounds. Two of the main constituents of wood are the cellulose polymers of glucose and the complex, highly branched lignin structures which are polymers of phenolic compounds with hydroxyalkyl side chains. The aim of the pulping step is to break down the ether links in the lignin while preserving the ether links in the long-chain cellulose polymers as much as possible.

The suspension of wood pulp in the reaction mixture is separated and the solid part washed. The filtrate and washings from the pulping process are combined as a ‘black liquor’. The washed residue, known as ‘brownstock’, now consists of cellulose fibres and up to 5% of residual, partly degraded lignin, which gives the crude pulp its brown colour. Further processing of this brownstock may involve a variety of steps often including bleaching, to provide either bleached or unbleached papers and boards with different finishes.

For many years, bleaching of wood pulp from the kraft process used sodium hypochlorite (NaOCl) or elemental chlorine (Cl_2) as oxidising agents to attack residual lignin in the wood pulp. This gave a bleached product with greatly reduced tendency to undergo yellowing later on. With these reagents, chlorine substitutes for hydrogen, especially on the aromatic rings of lignin, adds across carbon-carbon double bonds and oxidizes aliphatic side chains to carboxylic acids. This leads to the generation of organochlorine compounds in the effluent. Unfortunately, among these compounds are dioxins and a number of them are very unhealthy for the environment and toxic in human beings. As a result of concern over this, in the last quarter of the 20th Century there was a substantial reduction in the use of elemental chlorine for bleaching in the kraft process. It has been replaced by two main alternative bleaching processes:

- ECF (Elemental Chlorine Free) bleaching uses chlorine dioxide (ClO_2), which produces less chlorinated organic compounds and less dioxins.
- TCF (Totally Chlorine Free) bleaching avoids any use of chlorine or its reactive compounds and also uses less water. In a typical TCF process, the kraft pulp is treated with a sequence of oxidising agents to selectively break down the residual lignin.

Although TCF is less polluting, ECF bleaching remains the most widely used method for bleaching wood pulp: currently accounting for >90% of bleached Kraft pulp production globally.

Meanwhile, the black liquor formed from filtering and washing the wood pulp brownstock has been undergoing extensive treatment to recover components. This dilute solution is passed to a 'recovery boiler' and evaporated, yielding a volatile fraction from which methanol can be recovered for use as a biofuel (which will liberateCO2). After concentration of the black liquor it is combusted, and the heat generated is used to provide steam to operate the pulping stages and generate electricity, potentially making a pulp mill self-sufficient in energy – but also generating CO2 and SO2. After the combustion in the recovery boiler, the reside of hot molten sodium salts, mainly sulfide and carbonate, is run off, dissolved and passed to a 'causticising plant' and lime kiln, where reaction with calcium oxide followed by heating regenerates calcium oxide from the thermal decomposition of calcium carbonate, liberating CO2. It also provides a regenerated solution of 'white liquor' containing sodium sulfide and sodium hydroxide for re-use in the next pulping cycle. Overall, the recovery process has a good efficiency, but as well as recovering most of the sodium and two thirds of the energy content of the black liquor, it also generates substantial amounts of CO_2 and SO_2.

Moving forward from this point, we can continue developing the SOCME to map the ways that the bleached and unbleached products of paper and paperboard are used in a very wide variety of application and the ways in which matter and energy exchanges take place at every step from sourcing wood to disposing of the products. The SOCME provides many different entry points for focusing attention on parts of the overall system and for looking in detail at the chemistry involved and the impact on Earth systems.

Of course, we have not yet factored in the human systems involved, so let's add a few of those now. We might, for example, examine regulatory systems that relate to areas such as sustainable forestry, waste management or the control of chorine compounds in wastewater; we might think about how to reduce demand for paper caused by legal requirements and business practices, such as the need for hand-signed and witnessed documents or paper invoices and receipts, or the health, food and safety concerns that lead to disposable wrappings being used for certain types of applications.

We also need to consider the human angle of culture and fashion. To take one example, global consumption of toilet paper requires the logging of about 270,000 trees per day and this could be substantially reduced if people would generally use toilet paper made from recycled paper. Furthermore, many people prefer bleached white toilet paper to unbleached paper that can be brownish or greyish in colour. The impacts of bleaching and the release of organochlorine compounds into the environment could be substantially reduced simply by using unbleached toilet paper. People's preferences for printed materials such as books and newspapers similarly have very large environmental implications.

We can see that building the SOCME helps both to stimulate questions about connections and to illustrate connectivities and consequences. And this approach to seeing the total system rather than just some parts also provides a demonstration of this crucial aspect of emergence of systems properties, namely that sustainability is a property of the whole system and is not just a property of individual elements of the system. In the case of paper and paperboard, we see that industry claims of a near-perfect sustainability of these products has ignored some aspects such as the release of CO_2, SO_2 and organochlorine compounds into the environment and limitations in the actual scale of recycling.

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