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Material Metabolism: Reducing Risk through Flexible Formwork Substitution

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Abstract: For this special issue, sustainability and safety are discussed through the tropes of both material and work process substitution. As an architecture and industrial design team, we examine the potential of William McDonough's and Michael Braungart's "cradle to cradle" material methodology, and David Pye's "the workmanship of certainty" as relevant to the construction industry. Locating and revisiting the tenets of Gottfried Semper's *Stoffwechseltheorie*, alongside contemporary critiques, demonstrates that if historically, material and technique substitution led to architectural innovation, the same conditions exist today. To demonstrate a contemporary *Stoffwechsel* (material substitution) a formwork prototype was constructed at the University of Canberra's Workshop 7, by substituting timber with plastic, and 3D-printing the formwork. This prototype demonstrates a type of "technical nutrient" that is both recyclable as plastic, and reusable as formwork. This reveals the potential of substituting materials and processes not only to achieve material recovery, but rather, aiming for material recycling, reuse, or upcycling, therefore reducing socio-environmental risks in construction.

Keywords: cradle to cradle; concrete; digital design; formwork; Gottfried Semper; material substitution; plastic; prototype; recycling; risk reduction; *Stoffwechsel*; technique

Citation: Louw, M.; Farrah, S.; Maxwell, M.; Tomkins, S. Material Metabolism: Reducing Risk through Flexible Formwork Substitution. *Buildings* **2024**, *14*, 978. https://doi.org/10.3390/buildings14040978

Academic Editor: Yun Gao

Received: 28 February 2024
Revised: 21 March 2024
Accepted: 27 March 2024
Published: 2 April 2024

1. Introduction

1.1. Summary

This research is both textual and technical, and a critique of the way that these two modes of architectural research—theory and prototyping—tend to be separated. Through the lens of work and safety in construction, as outlined in this Special Issue, this paper begins with a literature review that defines the ethical (socio-environmental), social (safety in the workforce), and material dimensions (recycling and reuse) of our study. Research revealed three relevant theoretical frameworks to contextualise our contribution: McDonough and Braungart's definition of "technical nutrients" in relation to ethics and materials; Pye's "workmanship of certainty" in relation to safety, labour and digital prototyping; and Semper's theory of material substitution (*Stoffwechsel*), in relation to the ethical, social, and material dimensions.

From this theoretical grounding, we proceeded to test the viability of Polyethylene Terephthalate Glycol (PETG) plastic as formwork for concrete, advocating firstly for a cradle-to-cradle construction approach with a recyclable and reusable formwork; and secondly, for PETG plastic's ability to create complex forms using digital techniques to exhibit greater structural, labour, and material efficiency than traditional timber formwork methods. By fabricating a physical prototype of a concrete floor element at a 1:4 ratio, we were able to test the capacity of PETG plastic formwork to tolerate the weight of concrete in the casting process, to test its capacity for demoulding, and to confirm its ability to be reused.

1.2. Material Risk

Many risk-averse construction practices have negative consequences for the environment and by extension, society at large. It is well-known that the building industry is a large contributor towards carbon emissions and pollution, especially using standardised materials like concrete, steel, and aluminium. This is exacerbated by rampant consumerism and designed obsolescence, where the need for constant renewal generates additional waste. Buildings nowadays often have a lifespan of less than 30 years but are typically still constructed in ways that would allow them to last 100 years or more. The current concept of durability in the construction industry pertains to the desire for buildings or materials to withstand wear or weathering. However, while the most durable materials tend to be favoured, it is common that buildings do not reach their potential end of life. This, therefore, requires a reassessment of the concept of durability. For a more sustainable construction industry, we propose a different definition using formwork as an example: one that focuses on the durability of formwork material and process, rather than the formwork as product. The durability can be found in its potential temporariness and its ability to be extensively reused and recycled. Rather than focusing on the end of life of buildings, this paper aligns itself with the cradle-to-cradle approach and it argues that the durability of buildings or building materials should not be considered as finite or in "end-of-life" terms, but that their durability should be extended into their potential afterlife. Since Vitruvius posited *firmitas* (firmness) as one of the three elements of architecture, durability has been valorised, and while many of the materials used in building conform to this principle, the buildings themselves are often demolished long before their potential end of life. Furthermore, architecture's focus on durability ignores many interim yet consequential technical practices, such as jigs, falsework and formwork, temporary measures that nonetheless contribute significantly to waste and emissions.

Normative construction practices might carry less financial risk for developers and builders during initial construction (and the structures themselves might be quite safe during use), but when their materials are extracted, processed, transported, or discarded, they present a significant socio-environmental risk. Health and safety should not only be concerns during extraction, processing, and construction, but should be regarded in broader planetary carrying capacity terms. The health of society and the environment are interrelated, and as Susannah Hagan points out, "The ever-accelerating flow of matter—off the production line and onto the tip, briefly by way of the consumer—has led many to reflect not only upon the social costs of consumerism but also the environmental costs, which transform an industry's financial gains into a nation's financial losses—from pollution to ill health, climate change and overexploited resources" [1] (p. 253). The consideration of socio-environmental risk in terms of health and safety is inherently an ethical issue: when buildings need to be adapted, dismantled, or demolished, they carry risk for the workforce due to the processes required to separate materials and their resultant emissions, and when discarded, the environmental and societal risks are often significant. This is especially true when a building's constituting materials cannot generally be decomposed or recycled. Jacob raises the question "What happens when consumers start to question the conditions of those who make their buildings, just as many demand ethical conditions in the manufacturing of clothing, coffee and even smartphones?" [2] (p. 96).

Australia generated 25.2 million tonnes of waste associated with construction and demolition in 2020–2021, which is a 25% increase from 2016 to 2017, and it accounts for approximately a third of the net national quantity [3] (p. 44). Fortunately, the resource recovery rate has risen to 80%, and while there are still no viable alternatives to materials (such as concrete) for many types of construction, its energy use can be mitigated to some extent, and it does have recycling potential. One of the issues with concrete, however, is that a structure is essentially built three times: first, out of timber (i.e., formwork); second, using steel reinforcement bars and cages to mitigate bending stresses that concrete structures cannot sustain; and finally, out of concrete. Traditional formwork can only be used a few times for a very specific application, before it is discarded as construction and demolition waste. It is generally difficult to repurpose or recycle, and the glues and form linings used on the formwork do not easily biodegrade. Furthermore, formaldehyde adhesives are highly toxic and carry socio-environmental risk. The cost of erecting conventional formwork often exceeds the cost of the concrete itself, and it can be geometrically limiting. While it is positive that Australia's waste stream recovery in construction and demolition is significantly higher than many other countries [4] (p. 2), we propose not only recovery, but the possibility of recycling and reuse in the construction process.

As a case study, we have focused on a revaluation of traditional concrete formwork, by substituting both materials and methods, to reduce socio-environmental risk. The ecological footprint of normative construction is too high—the planet's carrying capacity is being challenged and its capacity to absorb waste or generate new resources is becoming increasingly difficult. For both a healthier work and natural environment, it is vital that the design and construction sectors reconsider normative design and construction processes, to not only be concerned with the safety of workmanship, but with the safety that the use of both materials and processes pose.

2. Material Substitution

2.1. Cradle-to-Cradle and Nutrient Cycles

The ideas presented here are not new, but the age of decarbonisation provides a suitable context in which to revisit them. One approach is to reconsider the concept of cradle-to-cradle design in relation to architecture and the inherent risks that buildings' constituting materials present. According to McDonough and Braungart, "Humans took substances from the Earth's crust and concentrated, altered, and synthesised them into vast quantities of material that cannot be safely returned to the soil. Now material flows can be divided into two categories: biological mass and technical—that is, industrial—mass" [5] (p. 2). They describe these material flows as consisting of biological and technical nutrients, where "Biological nutrients are useful to the biosphere, while technical nutrients are useful for what we call the *technosphere*, the system of industrial processes". In other words, biological nutrients are materials that are designed to return to the biological cycle by biodegrading (being consumed by animals and/or microorganisms), while technical nutrients can be returned into closed-loop technical cycles as nutrients for industry. Table 1 summarises a list of selected biological and technical architectural nutrients:

Table 1. Technical and biological nutrients in construction.

Technical Nutrients	Potential Technical Nutrients	Biological Nutrients
Steel Aluminium Copper	Thermoplastics: High Density Polyethylene (HDPE); Polyethylene terephthalate (PET); Polypropylene (PP)	Timber (untreated) Wool insulation Natural fibres (cotton; linen)

Metals were early technical nutrients in preindustrial societies, since they do not decompose easily, but can be melted down and reused. With the current proliferation of plastics and other composite materials in construction, these do need to be considered as technical nutrients that can be reused, or alternatively sequestered (like carbon) until industry develops ways of breaking them down successfully. Some products do not currently fit in either category, and McDonough and Braungart argue that this can create a dangerous situation. They describe a material such as PVC as an "unmarketable" which should be "…safely 'parked' until cost-effective detoxification technologies have evolved" [5] (p. 115). Disposing of them, or attempting to separate them effectively, can pose safety risks for the environment and for the workforce undertaking this disposal or separation. Cutting, grinding, granulating, and other means of separation to turn buildings or building elements back into biological or technical nutrients if they were not designed for it, could be hazardous. Designing for change, decomposition, disassembly, or nutrient separation is challenging but possible, although doing the same with existing building stock is more difficult.

Buildings and products are generally designed for obsolescence, so they need to be replaced regularly. However, they are generally not designed for effective reuse, repurposing or recycling to become useful technical nutrients. McDonough and Braungart specifically caution against nutrients that become mixed or contaminated with one another, which they refer to as "...Frankenstein products or (with apologies to Jane Jacobs) 'monstrous hybrids'—mixtures of materials both technical and biological, neither of which can be salvaged after their current lives" [5] (p. 99). This description can be applied to both in situ concrete with steel reinforcement, and generic timber formwork that does not make use of biodegradable glues and form linings, so while the timber can biodegrade easily and be returned to the biological nutrient cycle, the glues, resins, and form linings cannot easily be returned into the biological or technical nutrient cycles. They note that an advantage of nutrient isolation that prevents cross-contamination is that technical nutrients could then be upcycled rather than recycled or cross-cycled. Hagan regards the aim of buildings and products that are designed with due consideration for the environment as being modelled "... as closely as possible on the paradigm of the ecosystem... Energy is consumed, waste is produced and, instead of being thrown away, it is kept within the system. The detritus of a completed process becomes the raw material of a new process" [1] (p. 250). Unfortunately, these strategies and practices are not mainstream and are often referred to as "alternative" practices that must operate outside or on the periphery of standard construction codes due to the perceived risk that they represent.

Interestingly, several of the largest material contributors to construction and demolition waste are potential technical nutrients, such as metals (aluminium, steel), plastics, and glass, as well as biological nutrients, such as timber, garden organics, paper, and textiles [4] (p. 1). Where construction and demolition waste are usually managed locally, if designers consider reusing construction waste in the design process, with a focus on (i) material choice; and (ii) formwork techniques, designers can further reduce pressures on landfill, raw materials, and the environment.

2.2. The Workmanship of Risk and the Materials of Risk

In David Pye's well-known work *The nature and art of workmanship*, he posits the notions of *the workmanship of risk* and *the workmanship of certainty*. He describes the workmanship of risk as craftsmanship where the quality of the outcome is not predetermined, which depends on the "judgement, dexterity and care which the maker exercises as he works" [6] (p. 20). This he contrasts with the workmanship of certainty, which is often associated with mass production, where the process of making has been well tested, and where "the result is exactly predetermined before a single saleable thing is made". In the normative practice of design and construction, the materials and techniques that are used (such as reinforced concrete, standard steel sections, standard roofing sheets or cladding systems) are generally well-tested and specifiable through engineering and construction codes. Some of these are now also supported by "green" rating tools. In terms of workmanship, these materials and techniques would be classified by Pye under the workmanship of certainty: they are at the service of form. However, as mentioned above (and despite so-called green rating systems), they often present substantial risk to the environment and the health of the workforce and society more broadly, especially when they take the form of "monstrous hybrids". In terms of the safety hazards they pose, they could be classified as what we would like to posit as *the materials of risk*. In other words, when applied to the standard process of design where form is generated without sufficient consideration of materials as part of nutrient cycles, well-tested normative processes that could conform to the workmanship of certainty are, in fact, risky, due to the hazards they present to the environment and the workforce.

Construction methods must be found for developing materials and practices without either the inherent risk of workmanship, or the inherent risk of material. This paper suggests this can be achieved by adjusting standard design–construction workflows, and through material substitution of generic formwork with recyclable plastic. Pye, speaking about mass-production, mentions full automation as the workmanship of certainty in its purest state. Using digital design and making techniques, this principle can now be applied to mass customisation. Instead of generating form first and selecting materials to suit (which may pose a low risk of workmanship, but a high risk of material), one can now select materials that present a low environmental and health risk and develop techniques and elements through rapid prototyping using digital tools to shift closer to the workmanship of certainty. These prototypes can be used as a palette of materials and techniques to develop form digitally before developing the materials and techniques further until they present a low workmanship and material risk, and then preparing visualisations of the desired form based on this material knowledge. So instead of form followed by making (using a catalogue of standard materials or techniques), a reciprocal and continuous feedback loop can be generated where the process followed can be as shown in Figure 1.

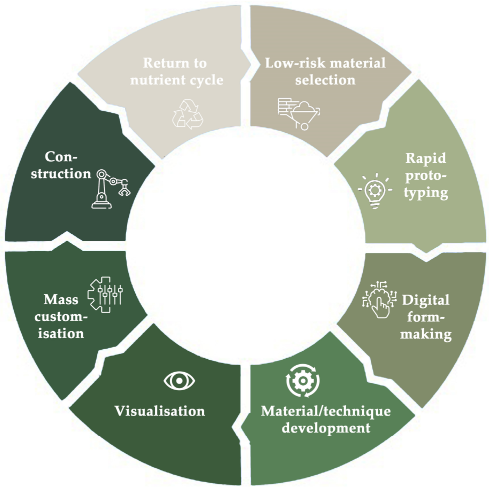

Figure 1. An improved workflow based on the principles of low-risk workmanship and materials.

Pye mentions that the most memorable works throughout history (except for the last few generations) were made through the workmanship of risk. For the safety of the environment and society at large, it will be necessary to shift to materials of certainty (not of risk), to accept the perceived workmanship risk of alternative ways of applying them, and through the adoption of emergent digital prototyping techniques reduce this sufficiently to make buildings that have a high degree of certainty in terms of workmanship and materials. McDonough and Braungart suggest that one should go beyond doing less harm or no harm, but that one should be designing with the purpose of improving the environment [5] (p. 108). The reality is that doing anything may have some negative consequences, and for the foreseeable future it may be that one would have to accept workmanship and materials of limited risk.

2.3. Gottfried Semper's Stoffwechseltheorie and Material Metamorphosis

McDonough and Braungart write that there is no such thing as waste in nature, because it is a system composed of different nutrients that form part of metabolic processes [5] (p. 92). Materials are finite since, in terms of matter, our planet is essentially a closed-loop system except for the occasional object that makes it through the atmosphere from space. Even though materials might change their state through metamorphosis to generate something "new", Hagan observes that "In nature, then, the 'new' is found in a transfer of matter from one form to another, all based on the same carbon". She proceeds to say that "It is a waste-not/want-not circular model of consumption found in what's left of 'nature'. . . The lower the amounts entering and leaving the building, the closer its metabolism is to the virtuous circle of the ecosystem—and the closer it is, the 'better' it is" [1] (pp. 250–251).

The concept of "good material" is a myth, as well as the concept of "only worked material has quality" [6] (p. 18). With recent developments in technology and materials research, alongside pressing environmental concerns, the Modernist misnomer about materials needs to be updated with a more appropriate framework. Gottfried Semper's concept of *Stoffwechsel*, which translates to metabolism, metamorphosis, or material substitution, provides a rich historical precedent to theorise our approach and prototyping [7] (p. 213).

Important to our focus on alternative formwork strategies is that *Stoffwechsel* occurs also in the transformation of technical processes, such as the development of various casting methods for bronze statues [7] (p. 109), [8]. Therefore, a substitution of conventional formwork with materials other than timber shoring—such as the plastics explored here—constitutes another aspect of *Stoffwechseltheorie*. The main difference in our approach from Semper's is in terms of his study of material metamorphoses from provisional to more enduring monumental structures. We propose a material transformation in reverse: a *Stoffwechsel* appropriate for an enduring environment through flexibility and constant renewal.

3. Application and Discussion

3.1. Materials: Material Substitution and PETG as Technical Nutrient

The fabrication of formwork is what drives achievable form in concrete. According to Meibodi, Voltl, and Craney, "The degree of geometric complexity a concrete element can assume is directly linked to our ability to fabricate its formwork" [9]. They argue that additive manufacturing, especially using Fused Deposition Modelling (FDM) with thermoplastics, expands the possibilities of concrete due to the ease with which it can be used to make freeform formwork. They also note that the lightness of the material makes it easy to transport, recycle, reuse, and remove. They do, however, caution that it will be challenging to use for large-scale construction due to the relatively slow 3D printing speed, that it can delaminate due to the hydrostatic pressure of the concrete, and removal can be difficult with complex geometries, amongst others.

Similarly, Burger, Lloret-Fritschi, Akermann, Schwendemann, Gramazio, and Kohler are of the opinion that 3D-printed formwork can improve concrete's sustainability, due to its ability to generate custom materially efficient elements [10] (p. 206). They also cite research that demonstrates how timber formwork can be used up to 20 times, whereas 3D-printed polymer can allow for up to 190 pours using a single form, which can then be recycled.

While experimental formwork systems comprising only biological nutrients—such as biodegradable hollow-core cardboard and upcycled 3D-printed sawdust—exist, the prototypes considered in this paper made use of Polyethylene Terephthalate Glycol (PETG) as a continuously reusable and cross-cyclable technical nutrient. PETG is a common thermoplastic and variant of PET, which was first synthesised by DuPont (USA) in the 1940s. It is the world's most recycled type of plastic and comes in either crystalline or amorphous form. Amorphous PET can be pelletised, making it suitable for extrusion processes such as those tested here. Adding glycol to it, to form PETG, makes it not only clearer, but more durable, ductile, stronger, and more resistant to chemicals and impact. It can also withstand higher temperatures, such as those that can be experienced during the curing of concrete, and it is fully recyclable. The proposed substitution aims to demonstrate how the challenges with conventional formwork can be addressed: It allows for the generation of complex geometries that are difficult if not impossible with conventional formwork. It uses less material, it is more affordable, it can be reused more times than conventional formwork, it can be recycled (and hence not discarded), and no nutrient separation is required with a direct return into the technical nutrient cycle. It also allows for decentralisation where, if recycled or recyclable PETG is available, and a suitable digital manufacturing tool can be procured, a large, specialised formwork manufacturing facility is not necessary.

While plastic remains an environmental dilemma, if it can be reused, recycled, cross-cycled or upcycled within a circular material economy until ways are found of breaking it down sustainably, it can at least contribute towards the technical nutrient cycle as a substitute for conventional materials.

3.2. Method: Modelling and Making

Standardisation can often result in excess materiality, technique, and tectonics. On this point, it is worth quoting Mario Carpo, outlining the benefits of digital technology in relation to architectural work and design:

"When form follows structural constraints, such as load and stress, standardization inevitably begets oversizing and wasted material. . . However, beams with uniform sections are cheaper to manufacture than beams with variable sections, especially when they are mass-produced off site. Consequently, beams are often uniformly sized according to the single point of maximum load, because the savings generated by mass-producing oversized but standardized beams are greater than the cost of the excess material. When this pattern is repeated in all parts of a large structure, the inevitable result is dumb structural design and a waste of building material. Indeed, both results characterized standard civil engineering throughout most of the second half of the twentieth-century. But this trend can now be reversed. Thanks to digital technologies, it is possible to envisage a new generation of nonstandard load-bearing components, both mass-produced and made to measure, and using no more material than is required at any given point of a structure" [11] (p. 104).

Despite his opening salvo, Carpo's commentary suggests that architectural form does not in fact follow structural constraint, but rather, is largely conditioned by the application of generalised design practices (i.e., drawing and calculation), simplified assembly logics (i.e., labour) and the inevitable standardisation of building materials, elements and components as they are increasingly commodified. Observing the negative impact work practices exert on design possibility is significant, as history offers numerous examples where the adoption of new design mediums has underpinned innovation and the realisation of exciting, non-standard, and yet highly efficient structural forms, especially with respect to concrete design and construction. Canonical examples include Heinz Isler's use of fabric formwork models; Antoní Gaudi and Frei Otto's use of physical computers in the form of hanging chains; and Felix Candela's implementation of ruled hyperbolic surfaces. As such, Carpo's nomination of the digital as a progressive medium through which to reimagine the "dumbness" of conventional practice is both well founded and not new.

Using a circular production process as shown in Figure 2, our methodology offers an example of the substitution of standardised formwork with flexible formwork through a design-to-fabrication approach that supports the realisation of complex double-curved concrete elements, such as precast floor slabs demonstrated here, enabled via the robotic fabrication of bespoke casting moulds (i.e., formwork).

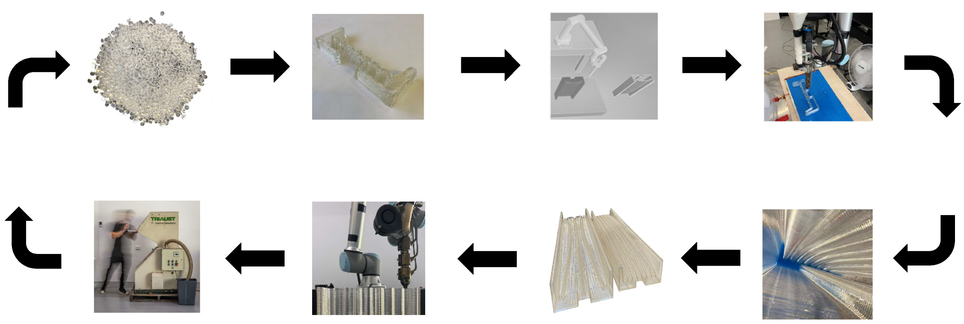

Figure 2. Images demonstrating the proof of concept based on the circular production process posited in Figure 1. Low-risk material selection, followed by rapid prototyping, digital form-making, material/technique development, visualisation, mass-customisation, construction, and return to the nutrient cycle.

Our work spans all aspects of this production chain: parametric design modelling, end-effector design (i.e., robot tooling), the automated generation of robotic instruction code, and performance testing through casting. The making of the formwork required a 640 metre toolpath, and the PETG was deposited with a 3 mm layer thickness. The size of the robot at our disposal allowed us to print the formwork for a 1:4 scale concrete slab element of 1500 mm length in two parts of 750 mm each with a total combined weight of 14.2 kg. At a cost of AUD8.00/kg, the total cost of the formwork was AUD 113.60. The total printing time for both parts was 9 h, which includes setting up. This was used to produce a double-curved unreinforced concrete slab element with an outside envelope of 1460 mm long × 420 mm wide × 130 mm thick (measured at the thickest part, vertical midline on the end cap plane) weighing 99.5 kg. With a ratio of 0.45 water/1 cement/3 sand/3 coarse aggregate (which was a mix of gravel and recycled crushed glass), this produced a concrete element with a strength of 20 MPa. It took three hours to mix and cast, and it was demoulded within 5 min after an initial curing period of 5 days.

3.3. Findings

Our work addresses the material and labour goals in multiple ways: Firstly, we employ a cradle-to-cradle material approach where embodied PETG is recovered, reground and reused from one casting mould to the next. This results in a near zero waste manufacturing approach. We suggest that customisable mould production is an important differentiator to existing precast practices which rely upon an economy of scale to recoup the investment of material and labour in the creation of project specific forms. Or conversely, projects must be standardised to employ commercially available systems. Instead, via the coupling of parametric design workflows to a robotic fabrication pipeline, we can produce unique moulds on a case-by-case manner. Be that from project-to-project or more granular again, from element-to-element. Secondly, additive manufacturing techniques by their very nature only deposit material when and where it is required, contributing to efficient, on-demand, and highly optimised production systems. This is especially relevant for complexly shaped casting moulds which historically make use of subtractive material strategies—specifically, Computer-Numerical-Control (CNC) routing which removes considerable material from stock material until a desired shape is realised. Often, such moulds are constructed from harmful and non-recyclable petrochemical materials, such as medium-density fibre board (MDF) or high-density foam. Thirdly, with a combination of PETG robotic extrusion and custom robotic tool pathing, we can produce forms that are not possible using traditional formwork methods and materials which typically comprise rigid boards. Finally, and perhaps most significantly, the realisation of double-curved concrete elements minimises bending and tensile stresses within the artefact, allowing for a reduction in steel reinforcement via a form-active design approach.

The key findings and insights from the 1:4 scale prototype are that it proves the viability of using 3D-printed PETG as a material substitute for traditional formwork, especially for the production of complex double-curved forms. As shown in Figure 3, PETG formwork with a 3 mm layer thickness has the capacity to support the medium of concrete with ease, and it demonstrates that demoulding is possible without having any adverse effect on the formwork material. The size of individual pieces of formwork is limited only by the size of the robot that is available, but this was overcome by using two lengths for the prototype, which could be increased for longer components.

Collectively, these attributes offer considerable material efficiencies, while the digital workflows that underpin them circumvent numerous labour bottlenecks and challenges associated with information control and exchange (i.e., communication, translation, and coordination) without the need to simplify design expression. Furthermore, these contributions only serve to extend the many well-understood benefits of traditional offsite production, specifically, enhanced material logistics and the promotion of a more controlled, and therefore safer, work environment. We suggest that the physical work samples offered here respond to Carpo's speculation on the agency of the digital in the critical reimagining of complexity, while offering a tangible example of the role of prototyping—digital and physical—that responds to Pye's workmanship of certainty.

The testing of alternative materials and processes through digital and analogue methods can contribute towards a reduction in socio-environmental risk. This research proves the efficacy of recycled PETG as a formwork material that can be reused more often than conventional formwork, and that it can then be recycled to manufacture and potentially mass-customise different complex forms. This cradle-to-cradle approach has an ethical dimension as mentioned earlier in this paper, since it demonstrates how less material can be used, how strain on the environment through waste that is difficult to separate into biological or technical nutrients can be reduced (which improves environmental health and hence societal health), and how it can contribute toward a healthier workforce through a reduction in the risk associated with toxic adhesives in conventional formwork.

Figure 3. An unreinforced 1.5 m long double-curved concrete component removed from formwork made via PETG robotic extrusion. The creased texture results from a vacuum-bag plastic lining that was used to facilitate demoulding and to protect the PETG.

While discussion of the contributions of this paper have largely centred on matters of material and labour efficiency, Carpo's ability to zoom out on their disciplinary consequence remains important. Releasing architecture from the constraints of standardisation emboldens us to consider the theoretical consequences of doing so. Hartoonian suggests the playfulness of digital methods allows one to explore "the notion of *economy of material*". While that is true, our prototypes also suggest it affords new orders of dexterity and expression, while in parallel, allowing for the considerable reduction in material in both the resulting artefact and its pre-form. Evaluated in this way, we suggest that digital formwork offers a tangible yet refurbished evolution of Semper's concept of metamorphosis, and perhaps parallel to what Hartoonian in his discussion of Zaha Hadid's work calls the transformation of "the heavy feeling of the concrete mass to appear as an agent of *light* architecture", "a metamorphosis" [12] (pp. 52, 64, 157).

4. Conclusions

The novelty of this research lies firstly in its bridging of architectural prototyping that employs digital design and manufacturing techniques with reflection on relevant established theory and literature: the consideration of the contribution of Gottfried Semper's *Stoffwechsel* theory, David Pye's writing on workmanship, and William McDonough's and Michael Braungart's "cradle to cradle" approach towards digital design, manufacturing, and prototyping in architecture is unique. Furthermore, the literature on health and safety or risk in construction is usually not considered in relation to digital design and manufacturing, and linking this to architectural theory and environmental considerations in particular serves to expand the scope of the paper beyond disciplinary boundaries. Using the theoretical underpinning to develop an improved workflow based on low-risk workmanship and materials, and to prove this through the development of a prototype using digital form-finding and robotic fabrication is breaking new ground, and the paper proves its efficacy through the successful completion of a 1:4 scale formwork element with a structurally efficient form that is arguably impossible with conventional formwork materials, and its resultant concrete floor element is shown in Figure 4.

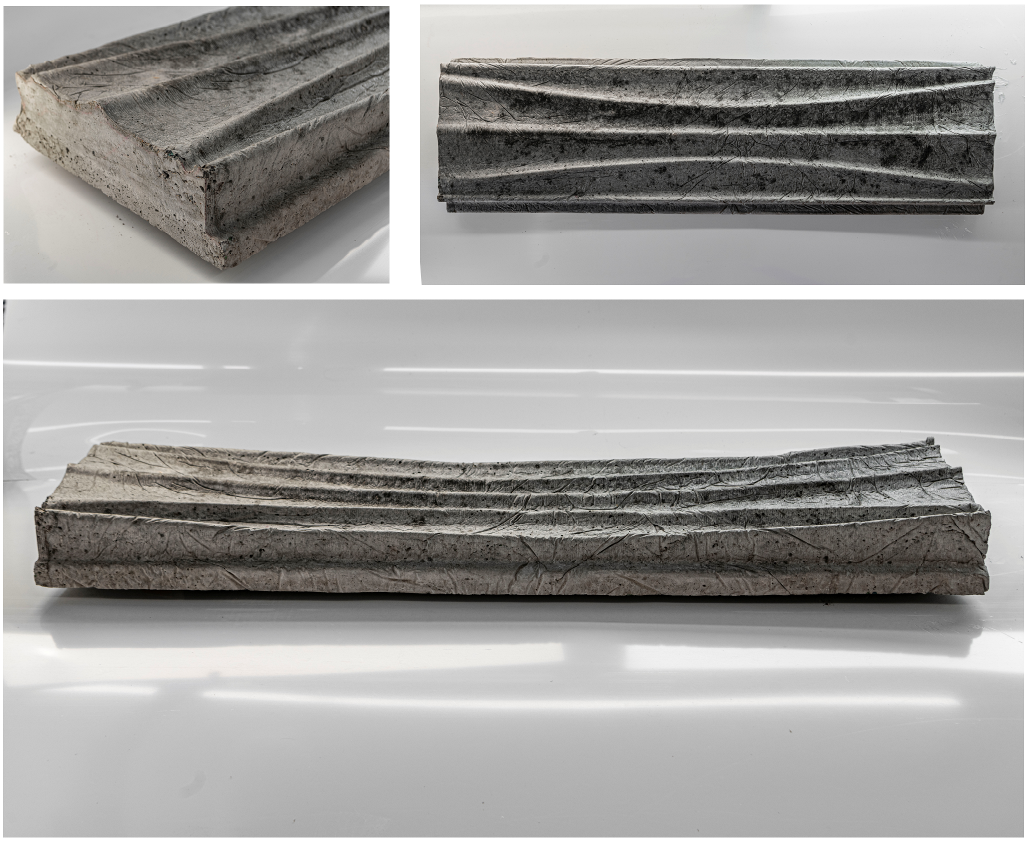

Figure 4. Images of a concrete component after removal from its PETG formwork demonstrating the dexterity and expression that the method offers, as opposed to traditional formwork.

The process of examining both construction materials and methods, as part of the discussion of *Stoffwechsel*, has resulted in a tectonic prototype which demonstrates how Semper's unique theorisation of construction is useful to both contemporary architectural theory and practice. Embracing digital design and construction methods can improve material and labour efficiencies in construction—and in formwork particularly—by using less labour during production, construction, and removal, enabling rapid form-finding before prototyping, using less material more efficiently, and using material that does not require nutrient separation afterwards. Through mass customisation and structural efficiency, economies of scale become irrelevant, which in turn reduce socio-environmental risk. Digital design methods recreate *disegno*—the act of simultaneously creating and conceptualising—and they allow for a contemporary and dialogical exploration between work and material, at the core of Semper's theory.

This research brings together three apparently disparate strands: a reflection on canonical architectural theory and literature, an argument for the need for cradle-to-cradle thinking to permeate the built environment—especially in terms of health and safety concerns, and testing these through the development of a physical prototype that was made using digital techniques. This addresses a current divergence in built environment research, and it is hoped that this study has illuminated the value in exploring these historic and contemporary trajectories in tandem. Several of the largest contributors to construction waste can be framed as technical or biological nutrients, and future work practices have to consider how this "waste" can be safely returned to nature, or how it can be recycled, cross-cycled, or even upcycled as part of the technical nutrient cycle.

Future Directions

Where the construction industry 4.0 focuses largely on the building product, we wish to further consider substitutes for building methods. Future directions of this research include experimental validation, the production of a 1:1 scale prototype in conjunction with industry partners, material tests for concrete aggregate substitutes, prototyping other flexible formwork materials that can be returned to the biological or technical nutrient cycle, and testing the forming of bio-based materials using the 3D-printed moulds. In the future, we hope to focus more on biological nutrients, which were outside the scope of this prototyping. These will result in similar tectonic expressions, where the "ornament" or process of material substitution is embodied in the digital technique. There is an ethical dimension to this exploration: by testing alternative materials and processes through both digital and analogue methods, the socio-environmental risk of the hidden stages of normative construction practices can be reduced.

Author Contributions: Conceptualisation: M.L., S.F., M.M. and S.T.; methodology: M.L., S.F., M.M. and S.T.; software: M.M.; validation: M.M. and S.T.; writing—original draft preparation: M.L., S.F. and M.M.; writing—review and editing: M.L., S.F. and M.M.; visualisation: M.M., funding acquisition: M.L.; component preparation: M.L., S.F. and S.T.; final component manufacture: M.L., S.F. All authors have read and agreed to the published version of the manuscript.

Funding: The work for this publication was made possible by Emerging Researcher Grant Funding from the University of Canberra's Faculty of Arts and Design. The open access journal processing fees were covered by an Open Access Journal Funding Grant from the University of Canberra's Faculty of Arts and Design.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding authors.

Acknowledgments: Jonathan Le Chung as research assistant, Amy Wei (FAD Materials Laboratory, University of Canberra for manufacturing assistance), Sam Shellard and Bill Shelley (FAD Workshop 7, University of Canberra for manufacturing assistance), Nick Burrows (FAD Workshop 7, photography of component for Figure 4).

Conflicts of Interest: The authors declare no conflicts of interest.

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