1. **Introduction**

This paper provides a theoretical and conceptual evaluation of the merits of a potentially applicable design framework known as Value Sensitive Design (VSD) for the responsible innovation of a speculative future technology called atomically precise manufacturing (APM). VSD is a philosophically predicated methodology to technological design that aims to account for human values early on, and throughout the design process of technologies. Likewise, APM is the assembly of materials whereby objects are built atom-by-atom. APM is controversial, with some experts doubting its feasibility (R. Baum, 2003; Jones, 2005b, 2005a; Zare, 2004) and others worrying about harmful consequences if APM is achieved (Auffan et al., 2009; Baumberg et al., 2007; Joy, 2000; Phoenix & Drexler, 2004; Snir, 2008). However, the best-case scenarios are dramatic, featuring benefits predicted to be on par with the industrial and computer revolutions (Drexler, 2013b; Freitas, 1999).

APM is one form of nanotechnology. Indeed, the term “nanotechnology” was coined by Norio Taniguchi in 1974 and developed in greater depth in K. Eric Drexler’s 1986 APM book *Engines of Creation*. (The APM concept dates to Richard Feynman’s 1959 talk “There’s Plenty of Room at the Bottom.”) Today, most nanotechnology research and development (R&D) is not APM, but instead is technology involving simpler nanometer-scale processes; this is sometimes referred to as ‘normal nanotechnology’ (O’Mathuna, 2009). Many nanotechnology researchers likewise doubt the feasibility of APM and instead favor research on more directly promising nanotechnology directions (e.g., Baum 2003; Nordmann 2007, 2014; Nordmann and Rip 2009; Grunwald 2010; Roache 2008; Ferrari, Coenen, and Grunwald 2012; Michelfelder 2011; King, Whitaker, and Jones 2011; Racine et al. 2014). Despite these doubts, current investments and national interests towards the development of APM (Jones, 2014; Lewis, 2016) warrant investigations into how we can ensure the concept, and its convergences with other technologies, is as beneficial to humanity as possible by intervening at the design stages and incorporating the relevant values necessary to achieve a desired end.

Additionally, the research has expressed criticism regarding the value and resources exhausted towards ethical speculation on advanced nanotechnology in favour of more immediate nanotechnology concerns (i.e., Nordmann 2007; Grunwald 2010). Three potential responses can be levied to these concerns. Firstly, arguments can be made that rudimentary forms of APM are existent such as biomolecules and ribosomes and they provide a solid foundation for more advanced APM forms (Freitas & Merkle, 2004). Secondly, persuasive arguments have been proposed by Roache (2008) arguing for the merits of speculative ethics for future technologies given their governability being more manageable in the early stages rather than *ex-post-facto* regulatory measures (see also Collingridge 1980 for arguments why anticipatory analysis of technology is critical). Similarly, although speculative future technologies pose many uncertainties, attention is warranted when the potential impact of those uncertainties prove conceptually large enough (Ćirković, 2012). To this end, I argue that continued ethical speculation on nanotechnology is of value, particularly in analyses that provide novel and potentially fruitful design pathways towards desirable futures.[[1]](#footnote-1)

To the best of my knowledge, this paper is the first to evaluate the merits of the VSD framework on APM R&D. Prior literature on APM has focused on its feasibility (Drexler, 1986; Freitas, 1999; Freitas & Merkle, 2004; Haggstrom, 2016; Huang, Chen, Chen, & Roco, 2004; Roco, 2011; Ross, 2007) and on the implications if it is achieved (J Altmann, 2005; Drexler, 2013b; Dupuy & Grinbaum, 2007; Freitas, 2006, 2007; Hansson, 2004; Harmon, Yen, & Tang, 2011; Hughes, 2007; McCray, 2012; Umbrello & Baum, 2018). These studies provide useful information but do not fully integrate the effects of stakeholders and the inclusion of values in the early design stages. Similarly, unlike other research projects that focus on a particular application or subdomain of nanotechnology such as (Timmermans, Zhao, & van den Hoven, 2011) or nanofoods (te Kulve, Konrad, Alvial Palavicino, & Walhout, 2013; te Kulve & Rip, 2011), the decision to focus on APM and its potential impacts should not be misconstrued as an overly general analysis, but instead a widening of the speculative circle of a *particular* form of nanotechnology in order to more comprehensively assess the merits of early design phase interventions (see for example Umbrello and Baum 2018).

VSD takes as its initial premise that technology is not value-neutral, but instead is sensitive to the values held by stakeholders, such as the designers, engineers, and users, among others (Friedman & Kahn Jr., 2002; Timmermans et al., 2011; van den Hoven & Weckert, 2008). By doing so, the value sensitive methodology aims to incorporate stakeholder values at the early design phases in order to direct the design and development of the technology in such a way as to successfully map the values.

Discussions surrounding APM R&D resemble decisions for other high-stakes speculative future technologies such as some forms of biotechnology, information and communication technologies (ICT), and artificial superintelligence (ASI). These technologies could be game-changers in their respective sectors, yet they each have impacts on the development and design of each other. The example of ASI is especially relevant because some believe it could have catastrophic results (e.g., Bostrom 2014), the same holds for APM. The possibility of either immense good or immense bad creates a ‘great downside dilemma’ (Baum 2014) for both APM and ASI. Thus a need to determine how technologies like APM effect stakeholders need to be taken into consideration to inform how to address the conceptual, empirical, and technical facets of the technology at an early developmental stage and incorporate the values that will produce the most beneficial product and reduce the likelihood of any potential harms.

This paper is meant to serve as an example of how the application of a VSD methodology could be used to design and develop safe future nanotechnology. In doing so, it is clear that APM and other advanced types of nanotechnologies and their speculated impacts remain nothing other than a potential future amongst many alternatives, and in some cases, entirely contrary possible futures. Hence, rather than aiming to provide routine ethical inquiry on issues of immediate and existent nanotechnology, this paper instead seeks to serve as a tool that further research could employ in making vision assessments (i.e., conceptualizing benefits/risks) of speculative technology and provide an explorative framework for the design process. Thus, this paper does not make claims about the technological feasibility of APM nor does it engage in the epistemological deconstruction[[2]](#footnote-2) characterized by speculative vision assessments. Instead its objective is to supplement those endeavours (Ferrari et al., 2012). Additionally, it makes no claims on the exclusivity of VSD as *the* design approach of APM among the various existing methodologies for responsible innovation. Instead, its aim is more humbly to propose VSD as a candidate for APM design.

Section 2. looks at APM as a conceptual technology, how it has been theorized to function with particular emphasis on its effects on a selection of technologies such as biotechnology, artificial intelligence (AI), and ICT, thus demonstrating the convergence effect of APM. The convergence effect of APM intensifies ethical concerns and also raises new ethical issues that do not currently exist within traditional manufacturing practices and technologies. Section 3. of the paper, taking into account the unique ethical issues, will introduce the VSD approach. This is followed by Section 4. where the VSD framework is argued for in greater detail. Section 5. concludes this paper by proposing potential design implications for the VSD approach that may serve as integral to the acceptance of APM systems; as well as future research avenues in the applicability of VSD to APM.

1. **APM and Convergence Factors**

The progress of APM, though currently still in its theoretical phases, is being halted by technological barriers. In spite of this holdup, the emergence of such a means of production raises impactful ethical issues, some of which have been discussed in the literature since its theoretical inception (e.g., Drexler 2013a; 2013b; Joy 2000). The attractiveness of APM is in the very nature of its ability to construct both nanoscale structures and systems, as well as macro-level structures with atomic precision, thus tightly controlling the material used, increasing construction tolerance, and controlling the byproducts based on the substances used (Drexler 2013a). K. Eric Drexler theorizes that APM systems have the potential to usher in an era of what he calls *radical abundance,* on account of its ability to mass-produce products at high volumes, at high tolerances, and at little to no cost. Such potential, he argues, would solve a myriad of global issues such as poverty, disease, and famine (Drexler 2013a; 2013b; Drexler and Pamlin 2013).[[3]](#footnote-3)

Although such utopian claims are theoretically feasible, as a consequence of APM's functional ability, they are far from logical necessity. Apart from APM's theoretical boons, there exists a host of potential catastrophic harms that could result from APM's development and misuse. Instances such as APM's ability to create affordable, mass-produced, hi-precision weapons could theoretically lower the threshold for armed conflict (Altmann 2005; Drexler 2013a). Examples of supposed weapons include nano-swarms of autonomous nanorobotics that can stealthily infiltrate an neutralize targets without human supervision (Krishnan, 2009; Nasu & Faunce, 2010). Likewise, APM could be used to create microscopic cameras that are both cost-efficient as well as highly effective, thus resulting in the potential exacerbation of mass-surveillance programs (Anissimov et al. 2008; Drexler 2007; 2013a; see also Ebbesen, Andersen, and Besenbacher 2006).

Regardless, the above dystopian examples of the possible impacts of APM are ones that characterize its effects on conventional or existing technologies, and although arguments can be made that they have different emerging forms, such technologies such as conventional munitions and camera surveillance already exist in some form and APM will serve to exacerbate the issues associated with them. Although there are issues that arise as a consequence of APM’s impact on current domains, this paper will also account for the emergent ethical issues that surface as a result of technological convergence.

* 1. **Convergence**

APM, as a token form of nanotechnology in general, is one of the leading technologies that scholars claim possesses a converging character (Houdy, Lahmani, and Marano 2011; Roco et al. 2013; see also Timmermans, Zhao, and van den Hoven 2011). The other technologies with which nanotechnology converges are biotechnology, information technology, and cognitive technologies – together these form the ‘NBIC’ technologies (Roco et al. 2013; Canton 2006; Roco 2005b, 2008; Jürgen Altmann 2005).[[4]](#footnote-4) Each of these formerly distinct fields, being functionally and operationally different, albeit with natural overlap or sharing, converge in the sense that they become synergistic with one another as they merge. Each of them ultimately becomes integral to the innovation and function of the other (Houdy et al., 2011). This trend towards the indiscrimination of domains raises new ethical concerns that did not exist in each of the fields as they existed independently (Houdy et al., 2011; Sandberg & Bostrom, 2006). As a result, a blurring of once distinct lines begins to emerge, and the liabilities and responsibilities start to shift on to designers rather than users. Because of this, an imperative arises that requires us to reevaluate how we incorporate ethics in design practices in order to account for these emergent value-changes.

In the discussion that follows, issues that arise at the point of convergence of APM with other NBICs will be examined. Although some normal nanotechnology is already seeing use in fields like biotechnology (e.g., Timmermans, Zhao, and van den Hoven 2011), the goal of APM and the revolutions associated with its development remain in the future, if at all possible. Although some of the potential implication of convergence that is discussed in the literature will be addressed, it remains uncertain which, if any, of the ethical issues that arise will come to fruition. Regardless of whether or not any of the issues discussed will be realized, they may still be informative on putting speculation into action (Grunwald, 2010). Likewise, the methodology proposed in this paper for addressing the potential concerns, although developed for application to domains other than nanotechnology, is nonetheless not exclusive to those domains, but instead serve as a general means by which researchers can incorporate values in the early stages of design.

* + 1. **Convergence with Biotechnology**

One of the most promising areas of innovation in the convergence of NBIC technologies is that of biotechnology and nanotechnology. Already, normal nanotechnology has found applications in the medical domain. One natural application of this intersection is the use of nanotechnology to miniaturize health care technology such as diagnostic equipment that can aid medical experts in accurately targeting areas of concern in an individual. Coupled with advances in ICT, such miniaturized devices would give doctors and researchers unprecedented access to a subjects’ real-time diagnostics (Weston & Hood, 2004).

Further, some scientists and engineers working with nanotechnology and tool miniaturization have proposed medical techniques that go even further. They have suggested the injection of autonomous and autonomic devices that can remain, diagnose, and treat whichever maladies they are programmed to look for. These theoretical systems have been referred to as ‘Doctor in a Cell' systems, and they are currently research in development (Casci, 2004; Maojo, Martin-Sanchez, Kulikowski, Rodriguez-Paton, & Fritts, 2010; Timmermans et al., 2011). Devices such as these are referred to as ‘borderline products' on account of the difficulty, if not the impossibility, of clearly categorizing their status (Timmermans et al., 2011). This applies in particular when looking at the classifications of drugs, drug delivery systems, and medical technologies. The convergence of nanotechnology with biotechnology has, and will continue to, put pressure on existent regulatory frameworks since traditional governance structures may be ill-suited to regulate innovations and the gap that once separated the different domains starts to fade (D’Silva & van Calster, 2009; Forsberg, 2012).

Not only are legislators and state actors affected by the closing gaps, but also direct stakeholders who directly interact with the technology like designers, patients, and doctors, as well as indirect stakeholders such as the general public, industry, etc. (Timmermans et al., 2011). Thus, to accurately lay out a successful design framework, whether that is via VSD or other potentially applicable approaches, it is critical to account for all the stakeholders, both directly and indirectly, affected by an emerging and converging technology. Hence, legislators, along with the researchers and developers of these nano-biotechnologies, the medical experts who put them into practice, as well as the patients’ subject to the technology make up the stakeholder population group. Therefore, as the convergence deepens, so too does the reliance on the accuracy, efficiency, and reliability of the technology itself and its place within medicine. The way medicine itself is practiced, how medical professionals work and respond to situations changes as they begin to lose control of how these technologies may affect and respond to a subject’s particular health condition. Questions of liability naturally arise and a trend towards seeing the developer and designer of the technology as the one who possesses the onus of responsibility. Given this shift, it is only natural that an anticipatory strategy is necessary where the design stage of a particular technology is addressed in order to incorporate the values of stakeholders.

* + 1. **Convergence with Information and Communication Technologies**

One of the chief worries surrounding the development of nanotechnology is its potential applications to information and communication technologies, particularly in its application in the surveillance and security domains (van den Hoven, 2014). Like many security technologies, they can be utilized to meet both beneficial and malicious ends. APM-enabled surveillance technologies could in theory aid in the detection and monitoring of rogue actors, as well as general criminal activity within a society, thus assisting in reducing their occurrences and effects (Umbrello & Baum, 2018; van den Hoven, 2014).

However, the development and implementation of surveillance technologies and programs is a highly contentious topic that may, in fact, be exacerbated by the introduction of APM. APM techniques can be used to decrease the size, increase the effectiveness and reduce the cost of computer systems that can then be utilized for the implementation of surveillance networks (Drexler 2013a; see also Cacciatore, Scheufele, and Corley 2011; Monahan and Wall 2002) [increase in computing is discussed further in Section 2.1.3]. Likewise, these incredibly powerful surveillance networks would work in synchronicity with APM created sensors and surveillance devices. These devices, just like the networks that they are connected to, could be minuscule and hard to detect, highly capable and manufactured in vast quantities and at a low cost. For example, a potential scenario was thought up by Anissimov et al. (2008) that describes the utilization of APM technologies to fabricate millions of hard-to-detect surveillance devices. These devices would initially be used for the purposes of foreign intelligence but later put to use in the domestic sphere under the façade of homeland security, thus affecting stakeholders, both direct and indirect, at international and domestic levels.

The most significant fear is that the ease by which APM-enabled surveillance technologies could be implemented, coupled with the attraction of their low-cost, would lower the threshold for their use in oppressive ways. There are apparent tendencies by already oppressive regimes to harness their surveillance capacity to monitor their state's citizens to ensure compliance and, if such situations arise, suppress any dissent. APM technologies, if designed in such a way that they permit this sort of technology to be manufactured by anyone with ease would only serve to exacerbate the oppression of populations. In fact, Bostom (2014) proposed a catastrophic scenario involving global oppression. This worst-case scenario would be one in which collaborating world governments or the formation of a single world government employs oppressive practices that utilize these APM surveillance technologies. The vastness of such a government's reach, both as a function of its geopolitical scope as well as the extent of its surveillance program, would be nearly impossible to overturn by any conventional means. However, Bostrom does account that if such technologies are sufficiently available to other agents and populations, then such a catastrophic scenario is rendered unlikely to occur. Likewise, the scope to which these technologies can be created can also be considered to be a function of the design of the APM assemblers. Built-in restrictions, physical limitations rather than malleable programming could go a long way to mitigating many of the adverse products that APM could create, both for surveillance and the other technologies discussed in this paper.

* + 1. **Convergence with Artificial Intelligence**

In looking at the developments and projections of AI, considerations of how APM will affect its development, and in some cases how AI will influence the development of APM is of particular interest. Like APM, AI is considered by many experts to be a risky technology given the drastic ways in which AI can affect stakeholders (Bostrom, 2014; Joy, 2000). In this discussion of AI and APM, the AI mentioned is not the AI that currently exists today, which, although highly intelligent, is only so in a very narrow way. Instead, the AI that is of particular interest in this paper is artificial general intelligence (AGI), which is intelligent across many domains; and artificial superintelligence (ASI), which possesses intelligence at a degree and scope that far outpace any human capacity.

One risk associated with AI is termed a hard takeoff, occurring when an AI self-improves, that is, faster than its designers can train the AI with desirable characteristics (Barrett & Baum, 2017a, 2017b). One main causal factor associated with the potential of a hard takeoff is computing power. A ‘seed AI' that is present on an adequately advanced computing system can recursively self-improve to the point where it engages in a hard takeoff into ASI. Consequentially, the lack of sufficient time that humans have in training a self-improving AI with beneficial behaviours can ultimately lead to negative global consequences (Bostrom, 2014)

APM plays directly into the risks associated with a hard takeoff given its ability to construct computing systems in such a way as to increase the computing potential relative to size. Some researchers have thus argued that the development of APM before the development of beneficial AI would increase the potential for adverse consequences in AI (Bostrom 2012, 2014; Goertzel 2016; Goertzel and Pitt 2012; see also Shulman and Sandberg 2010). As a consequence, Bostrom (2014) argues that it would actually be beneficial if AI were developed before APM, not solely for the possibility that APM increases the risk of an ASI takeoff, but that the creation of a beneficial AI would aid in reducing risks associated with APM development and use (see Yudkowsky 2008; Clark 2010).

The development of APM for advanced computer hardware, particularly to provide the material base for powerful and innovative AI systems, could affect stakeholders in dramatically new ways. How APM systems themselves are designed and programmed for change the relationship that AI developers have with their research. Not only are liability burdens shifted away from AI researchers, but the changing nature of computing as a direct result of APM's influence begins to change the nature of responsibility and who possesses it. Additionally, if the risk of a hard takeoff from a seed AI is high enough, meaning that it could occur relatively simply because of the exponential increase in computing power from APM products, then risks may also increase for ordinary citizens if given access to specific APM technologies.

Once again, the stakeholders such as the AI designers, investors, and the general public who are affected by the development of these emerging and converging technologies become of particular importance. Because they have a particular stake in the game, as stakeholders, it is the responsibility of innovators to account for the values that they share during the early design phases of innovation in order to ensure the highest likelihood that those values will be expressed once a technology is rolled out and becomes ubiquitous for use. It is for this very reason that this paper aims to introduce a design framework that proposes a transparent methodology for accounting for stakeholder values in responsible design. The following section outlines each of this theory, as well as how it could be used to address the risks of APM.

1. **Designing for Values**

The three examples of converging technologies discussed herein are far from exhaustive when regarding the impacts that nanotechnology could have on convergence. Whether it is doctors abdicating much of their medical interventions to new technologies or how citizens go about their day-to-day lives in a state that has ready access to advanced and intrusive surveillance devices, APM could have far-reaching implications for unaccounted stakeholders. Such a radical impact on members of society make the lack of participatory design practices in nanotechnology research worrisome.

The risks associated with APM can be mitigated, as argued here, through the implementation of value-based design methodology, more specifically, VSD. This framework arose from the realizations that two principal values were missing from the design process in technological innovation, user autonomy and freedom from bias (Briggs and Thomas 2015; Friedman and Kahn 2000; 2002). The purpose of VSD is to ensure that designers include the values held by stakeholders in the early design phases in order to not only produce a satisfactory product for the stakeholder, but one that ensures that human values are advanced in technological innovation (Friedman and Kahn Jr. 2000; Friedman et al. 2013; Nathan et al. 2008; van den Hoven and Manders-Huits 2009).

The emphasis on the inclusion of human values is an urgent priority to make in the domain of converging technologies, as harmony between individual, corporate, and societal values are often not found. The above examples show how converging technologies promise great merits, but they can as easily create a dystopian future; this warrants for a design space that considers the values of all stakeholders that the technology may potentially impact.[[5]](#footnote-5) VSD makes explicit claims to help foster a participatory space in which stakeholders can communicate both their values and desires (Briggs & Thomas, 2015).

* 1. **Value Sensitive Design**

APM, being one of the most radical means by which nanotechnology could potentially intersect with other technologies, confronts many of the ethical concerns that face these other converging technologies as well as raises new issues. As developments in nanotechnology, in general, continue to garner massive federal financial support in the United States (Harper, 2011; NSTC, 2008; Roco, 2005a) and Europe (Berger, 2013; Case, 2011; Johnson, 2013), both the current issues as well as emergent ethical concerns will need to be addressed.[[6]](#footnote-6) The convergence of APM with biotechnology, for example, can allow for an unprecedented level of personalized control over medical diagnosis and treatment. This could ultimately shift discussions of liability away from the medical professionals and onto other stakeholders such as the technology designers and even the patients who use them (Timmermans et al., 2011). This convergence of APM with other technologies makes it increasingly difficult for experts who specialize in a single field to see the long-reaching implications associated with their technology's advances in different spheres and vice versa. This ambiguity and uncertainty, as well as the shifting of responsibility to the designers of technology, require us to reconsider how ethics should be incorporated in designing activities (van den Hoven, Miller, & Pogge, 2012). In all, as technology advances and converges, the stakes change and the burden of responsibility shifts.

This section suggests that VSD currently provides the most measured way of addressing this shift in responsible innovation and sufficiently incorporates the values of stakeholders in a way that is not considered in other design frameworks. Although it emerged from the field of Human-Computer Interaction, VSD has since been a methodology applied to other domains (Brey, 2010, 2014; Davis & Nathan, 2015; Oosterlaken, 2015; Reynolds & Picard, 2005; van Wynsberghe, 2013a; Vermaas, Tan, van den Hoven, Burgemeestre, & Hulstijn, 2010). The intent behind VSD is to foster the development of high stakes technologies while simultaneously accounting for the values of all relevant stakeholders during the early design phases (Friedman & Kahn Jr., 2002). Hence, the VSD methodology can provide APM and similar emerging and convergent technologies with a framework in which to incorporate ethics in the design phases while accounting for technological advancement and interdisciplinary scope (Cummings, 2006).

The VSD approach is based on the assumption that technology is something that is value-laden and thus is of significant ethical importance (Friedman et al., 2015; van den Hoven & Weckert, 2008). The approach puts considerable emphasis on the human values of freedom, autonomy, privacy, and equality (Davis & Nathan, 2015; Friedman, 1997). Each of these values has the potential to be limited by technology and thus must be taken into account during the design of technologies. Whereas other design philosophies such as the Inclusive Design framework seek to design technologies that are universally optimal by designing for societal extremes, the VSD approach focuses on the values of stakeholders and how those values can be reconciled with design and engineering limitations and constraints (Friedman, Kahn Jr., & Borning, 2006; Miller, Friedman, Jancke, & Gill, 2007; Timmermans et al., 2011; van den Hoven & Weckert, 2008). Rather than the traditional means of evaluating a technologies moral status, i.e., how it is placed, used, and construed in a societal context, VSD seeks to look at the impact that technology has on the moral landscape, determine the values of stakeholders, and integrate those values in the early design phases.

VSD, however, does not seek to revolutionize the engineering practices of designers in such a way that requires unique or burdensome requirements; instead, VSD is an instrument that proposes ways of changing existent designing and engineering methods in such a way as to include stakeholder values (Cummings, 2006; Verhagen, Dalibert, Lucivero, Timan, & Co, 2015). Given that the VSD methodology requires integration within the already practiced engineering and designing approaches, alliances of VSD in the design practices of APM would thus need a foundational understanding of the methods used for APM research and design.

Although APM is currently conceptual in nature, much work is being done in the general field of nanotechnology that is building the necessary foundation towards the potential development of APM (Freitas & Merkle, 2004). Thus, in order to apply the VSD approach, the current practices in the design and engineering of APM-relevant normal nanotechnology must be evaluated. VSD methodology is typically understood as a tripartite methodology consisting of conceptual, empirical, and technical investigations which all aid in determining the requirements set by a particular technology (Davis & Nathan, 2015; Friedman & Kahn Jr., 2002; Timmermans et al., 2011). Conceptual investigations may serve as a critical starting point. They aim to investigate the values that we wish to integrate into the design process. Not only this, but conceptual investigations determine how the technological constraints affect the values under consideration as well as the potential trade-offs that may arise amongst contending values (Friedman & Kahn Jr., 2002).

One issue that arises in the investigation of values is that of conflicting values as well as the strength of value origins (Alsheikh, Rode, & Lindley, 2011; Borning & Muller, 2012; Johri & Nair, 2011; Le Dantec, Poole, & Wyche, 2009; Manders-Huits, 2011). Accounting for the varying, and often conflicting set of both moral and non-moral values, the VSD framework is designed in such a way that requires these conflicting trade-offs to be considered both at the initial stages of design as well as throughout the design process as they emerge (Capurro, Longstaff, Hanney, & Secko, 2015; Friedman & Kahn Jr., 2002; Taebi, Correljé, Cuppen, Dignum, & Pesch, 2014). For example, the issue of safety vs. efficacy often emerges in the pharmaceutical industry, among other domains of technology. Timmermans et al. (2011) argue that such a case of *moral overload* can be addressed in the VSD approach (for a discussion of moral overload and trade-offs in technological design see Van den Hoven, Lokhorst, and Van de Poel 2012). However, this does not entail that all the tensions that arise between values can, or even should, be addressed when confronted (Miller et al., 2007; Nathan, Klasnja, & Friedman, 2007). The VSD approach aims to help illustrate the existence of any tensions which can then be addressed during other stages of design, if at all (Davis & Nathan, 2015; Nathan et al., 2007).

Additionally, there are VSD scholars that argue that the approach does have a normative element from which it bases objective values claiming that freedom, autonomy, privacy, and equality are instantiated in different forms across different population groups (Friedman, 1997; Timmermans et al., 2011). Although the issue of values, their origins, and their strengths are of vital importance to the adoption and success of a VSD approach, it is not the aim of this paper to provide a comprehensive philosophical analysis of value investigations (for a novel approach to the strength of these investiggations see Umbrello, 2018). Instead, future research projects should investigate the position and relevance of moral philosophy and psychology in the VSD framework.[[7]](#footnote-7)

An example of the application of the VSD framework to APM is in the development of APM ‘productive replicators’, which are manufacturing systems capable of not only self-replication but also the assembly of non-self-objects (Freitas & Merkle, 2004). In the design phases, obvious ethical trade-offs are confronted, between the efficacy of the assembler and safety of the potential products to be manufactured. The safety factor relates to insuring the products produced do not cause personal or societal harm; this applies in particular outside the military context where citizens could have access to assemblers. The ability to provide therapeutic medicines for beneficial reasons is as plausible as the production of weaponized viruses on systems designed with limited physical constraints. Efficacy, on the other hand, looks at the extent to which the assemblers can create beneficial products. Trade-offs may arise in effectiveness itself as restricting one form of the potential outcome (e.g. biological weapons) may limit the ability to produce others (e.g., medicines). VSD provides a means by which designers can balance these trade-offs by taking into account the different values of stakeholders and using the philosophical literature available to justify the proposed values against technological constraints (Friedman & Kahn Jr., 2002; Timmermans et al., 2011; van den Hoven, Lokhorst, et al., 2012). Multiple scholars have already proposed ways in which the ethical literature may be used in the design phases of responsible innovation (e.g., Cummings 2006; Friedman and Kahn Jr. 2002; Davis and Nathan 2015).

The VSD methodology can also be drawn upon in order to aid researchers and designers in complying with existent governance frameworks that aim to regulate the conduct of developers of nanotechnology. An example of such official governance structures is the European Commission’s Regulatory Aspects of Nanomaterials (Commission, 2008; Galiay, 2011) or more unofficial governance frameworks like the Foresight Institute’s Guidelines for Responsible Nanotechnology Development (Jacobstein 2006; see also Guston 2014) and the Nanoshield proposal forwarded by Michael Vassar and Robert A. Freitas Jr. (Vassar & Freitas, 2013). The former’s guidelines of conduct explicitly regard the values of openness and inclusivity of all stakeholders as paramount amongst other values (Commission, 2008). As mentioned, the inclusion of stakeholders as part of the VSD framework is critical to determining the values to be considered during the design phases. Both direct stakeholders (i.e. those who design and develop APM) and indirect stakeholders (i.e. citizens, users of the APM) must all be included in the conceptualization stage of VSD methodology to ensure that all those who are potentially affected by the technology can express their values and concerns. In taking into account all of the relevant stakeholders, we can discern a clearer vision of the impact that APM will have and how its development can be tailored to result in a beneficial product.

The second essential stage of VSD is that of empirical investigations. Current manufacturing practices and regulations must be taken into account, particularly their applicability to APM techniques. Naturally, areas of overlap will exist, and perhaps existent regulatory frameworks will be sufficient to cover them. However, APM is a converging technology and thus not only may current issues in manufacturing practices be exacerbated, but so too those issues that arise from the overlap of the converging domains (Bawa & Johnson, 2009; Houdy et al., 2011). The VSD approach allows for the values that emerge from this convergence to be taken into account during the design phases in order to cover the emerging ethical issues that arise. Hence, not only how nanotechnology affects NBIC technologies must be taken into consideration, but also how the other NBIC technologies change APM. In doing this, the testing practices characterized under the empirical investigations stage of VSD will aid to broaden both the current and future testing practices of APM (Friedman & Kahn Jr., 2002) as well as serve as a means of checking the strength of the initial conceptual investigations and how those instantiated values map on to real applications (Borning & Muller, 2012; Davis & Nathan, 2015).

For the VSD approach to be successful in integrating the values of stakeholders at the design phase, nanotechnology specialists must take up the VSD approach and inform the framework in a way that makes it specifically tailored to their domain. This will involve nanotechnology researchers drawing upon existing practices and integrating them into VSD methodology. This manipulation of the VSD approach, informed by the specific domain to which it has been applied, has been a subject of the VSD literature since its inception (e.g., Briggs and Thomas 2015; Dechesne, Warnier, and van den Hoven 2013; Warnier, Dechesne, and Brazier 2014; Friedman and Kahn Jr. 2000; van den Hoven 2014; van Wynsberghe 2013; Royakkers and Steen 2017; Aad Correljé, Eefje Cuppen, Marloes Dignum 2015).

Further research projects should engage with the VSD literature and case studies in order to determine the most practical policy frameworks that provide incentives and other tractable steps for the implementation of VSD in this capacity. Additionally, future research should aim to incorporate analyses of current nanotechnology initiatives as well as what regulatory structures currently exist and how those affect industries. This research is necessary given that doing otherwise may appear as a demand on venture capitalists, researchers and stakeholders involved in development to ignore very concrete profit motives and market forces, and instead to spend time on abstract ethical principles that would (in their view) put them at a disadvantage to their competition in bringing products to market quickly; asking them to do that seems unlikely to achieve much. Hence, in order to more efficiently incorporate values in design via a VSD framework researchers need to engage in holistic vision analyses rather than exclusively ethical ones.

1. **Empirical Studies in the Right Directions**

The theoretical basis for the application of VSD to speculative nanotechnology, i.e., APM, encompasses the bulk of this paper. However, the last decade has produced critical empirical scholarship concerning stakeholder participation, co-creation processes, and the moral assessment of nanotechnology. Because it is this paper’s contention that the transformative nature of speculative nanotechnology requires early stage value assessment and integration, it is essential to acknowledge the empirical progress towards such a goal. As such, this section aims to briefly outline some of the vital work that has been undertaken that can be levied towards this end. Although not all of the work is directly focused on APM, APM is nonetheless the projected future goal of nanotechnology research. To this end, looking at the design of the early stages of nanotechnology is the goal of anticipatory research.

An early technological assessment was conducted in 2006 by van Merkerk and Robinson that investigated the socio-technical dynamics of lab-on-a-chip technology and how the variable nature of researchers and technologies influence the path to the emergence of a technology (van Merkerk & Robinson, 2006). Similarly, Lucivero et al. (2011) explored the variable of technological desirability on the emergence of a particular technology. Conceptual investigations of VSD should be buttressed by the technical desirability assessment to determine the value of speculative technologies prior to ethically vacuous development (Lucivero, Swierstra, & Boenink, 2011). As such, the speculative elements that are typically characterized as ‘imaginative products,’ given the inherent uncertainty with emerging technologies, can be soberly abated by employing the tools and methods proposed in these studies.

Empirical studies such as these must be levied in order to successfully implement a design-for-values approach, whether that is VSD or otherwise given that they enroll real-world stakeholders. Other studies that clearly demonstrate the nuances of organizing and integrating stakeholder engagement include those undertaken by te Kulve and Rip (2011) applied to the emergence of nanotechnologies in the food packaging sector, Robinson (2009) engaged in a stakeholder workshop to inform responsible innovation on the co-evolution of nanotechnologies, and Krabbenborg (2013) successfully showed how the developmental trajectories of nanotechnologies can be influenced through stakeholder inquiries between various parties, in this case, between civil society organizations (CSOs) and technology developers (Krabbenborg, 2013; Robinson, 2009; te Kulve et al., 2013; te Kulve & Rip, 2011). The latter empirical analysis proposes how a similar joint investigation of values can be employed on a more extensive societal scale viz. symmetrical deliberations of values and engagement in order to induce an effaceable risk reduction framework as exemplified by the DuPoint/EDF joint venture (Krabbenborg 2013; see also Krabbenborg and Mulder 2015). Regarding the ethical assessments of emerging technologies and their social impacts, scholars such as Dirk Stemerding, Tsjalling Swierstra, Marianne Boenink, and Aimee van Wynsberghe have produced empirical scholarship that may provide some clarity for nanotechnology. Stemerding et al. (2010) discuss the future ethical implications of genetic susceptibility screening and the ethical implications of such an emergence on society. They conclude that emerging technologies must be understood through the context of their interactions with moral developments (Stemerding, Swierstra, and Boenink 2010; see also Boenink, Swierstra, and Stemerding 2010). The study outlines a systematic approach to creating future scenarios that can help researchers and stakeholders to incorporate existing and potentially future values early on in precisely the same way that the VSD methodology prescribes.

Similarly, Aimee van Wynseberge has investigated the potential of integrating ethics in care robotics via the implementation of a tailored form of VSD which she terms Care Centered Value Sensitive Design (CCVSD). The normative basis of her research shows how this tailored form of VSD is particular to the health and care sector by drawing upon the traditional existent values that characterize healthcare (van Wynsberghe, 2013b). Her application is illustrative of how the VSD approach integrates within existing and developing frameworks. Successful integration means accounting for existing values, which she accounts and by doing so provides a means by which the methodology can be expanded outwards. She does this by investigating the applicability of the CCVSD methodology to robots outside the healthcare domain as well as pushed the boundaries of the methodology to ascertain the limits of its application (van Wynsberghe, 2016).

The empirical studies mentioned here are far from exhaustive; however, it was necessary to include some of the more central empirical studies to show that real-world research has and is still being conducted towards the goal of value-integration in the design and rollout of technologies. In doing so, this paper should serve as a springboard towards sober considerations regarding value integration in APM technologies and research.[[8]](#footnote-8)

1. **Design Principles and Policy Points**

The approach of this paper is to introduce the VSD methodology and its applicability to APM. Although other design approaches may, in fact, provide some useful perspectives in designing beneficial APM, VSD methodology provides a more holistic and systematic approach to designing beneficial APM. An essential part of this strategy is determining the values of stakeholders through conceptual investigations and, in particular, levying the existent empirical work on the subject. This section aims to list some of the potentially useful design principles that can be incorporated in the design phases of a VSD approach to APM. The following list is nowhere near exclusive nor exhaustive given the various avenues that technological convergence will lead, but instead, the values listed have been distilled from the existent philosophical and empirical literature and is intended to serve as an example of optimal design flows that would promote the acceptance of beneficial APM to stakeholders:

* *Proportionality*: designers should embrace a standard of proportionality and thus design APM systems that are physically limited to not manufacture weapons. This naturally must vary amongst users (i.e. civilian vs. military). Hence, balanced APM systems should be something that is openly promoted in order to limit over-engineering.
* *Security:* Users of APM systems should be informed about not only the limitations of their APM systems but also the vulnerabilities of those systems. This becomes particularly relevant as nanotechnology converges with ICT. Access to networks by remote means requires a minimum standard of both software and hardware security.
* *Safety*: Users of APM systems should be informed of any health threats that APM systems may pose during use.
* *Accessibility*: APM systems should be designed in such a way that fosters ubiquitous use given the above design flows. This is intended to limit exclusions based on socioeconomic status (SES), thus promoting a more egalitarian use of APM systems.

Examples already exist that are sensitive to these listed values. In fact, industry and policy work regarding financial technologies – or FinTech – are not only showing a trend towards better regulation but also the inclusion of values like proportionality regarding the information that they gather from their users, as well as a tendency toward offering greater accessibility as a function of the technology itself. Firstly, proportional considerations must be taken into account in the designing of APM technology. In doing so, designers seek to balance the potential benefits that the systems could produce against some of the risks associated with technological potential itself. In other words, APM systems should include physical barriers that enable specific materials to be used and determined products to be manufactured. The benefits that arise from constraints should be weighed against the potential loss of manufacturing potential. Second, as is true in the FinTech world, users are more willing to adopt and use systems if there is transparency regarding the potential hazards and vulnerabilities associated with adoption (Levy, 2016). Finally, the ubiquitous adoption of APM systems may hinge on their ability to be accessed and used by any member of society regardless of SES; thus design considerations for broad spectrum use must be accounted for during early developmental and conceptualization stages.

1. **Conclusions**

The introduction of APM systems will undoubtedly have dramatic effects both on current manufacturing practices, as well as other domains such as biotechnology, ICT, and cognitive technologies. In doing so APM and other nanotechnologies will exacerbate current ethical issues in addition to raising new ones. This paper explores a particular design approach that may be useful to consider when designing nanotechnology solutions; Value Sensitive Design, and it is proposed that VSD provides a means by which designers can consider all of the values and desires of stakeholders, weigh those values and incorporate chosen values during the design phases of APM before the technology becomes ubiquitous.

The continued convergence of the NBIC technologies comes with an inherent ambiguity. However, by acknowledging this ambiguity as a given, it can serve as a foundation for continued research into addressing the social and ethical concerns that will inevitably emerge from the convergence. Likewise, the convergence factor is likely to exacerbate existent ethical issues such as changes in liability in biotechnology, as well as the debates surrounding privacy and security (see Ebbesen, Andersen, and Besenbacher 2006). These existing issues, in and of themselves, warrant a design framework that is capable of recognizing these problems and conceptualizing the values of those who hold stakes in the outcome and bringing them to bear during the design phases.

The VSD approach provides such a framework that is capable of taking the current issues into account, conceptualizing the values of stakeholders, adapting itself to the particular domain of application and accounting for the inherent uncertainty of technological innovation. However, although the VSD framework is capable of being moulded to the specific application of APM and nanotechnology in general, it has yet to be accomplished entirely. This paper shows that not only is such a moulding theoretically possible but that some initial design flows can already be identified. Firstly, this article reveals that in suggesting the VSD approach ethical and societal issues surrounding nanotechnology can be interpreted as being value-sensitive. These values can be understood as primarily a function of the stakes held by those affected by the technology, i.e. the stakeholders. Additionally, it maintains that such stakeholder values can play a critical role in the design phases of the technology and can serve as a springboard for further conceptual explorative research. Finally, an essential part in the application of a VSD framework to an emerging technology is its ability to integrate current design practices, and to fill the voids that those practices may have in their application to emerging and converging technologies.

This paper, although failing to make any certain conclusions regarding the analysis of APM impacts or the approach of VSD applicability, shows that VSD may serve as a useful starting point for integrating the values of stakeholders in the design phases of APM, thus furthering the potential for beneficial APM technologies once they reach the market. What is required however is further research on how the VSD framework can incorporate current design practices and flows in nanotechnology research, how that research is and will change as technological innovation advances, as well as research into the emerging ethical and social issues that arise from the convergence of technologies.

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1. Desirable futures, in this case, is not intended to be taken as a universalism, but instead as a culturally/socially situated desirability. [↑](#footnote-ref-1)
2. For a description of epistemological issues in technology assessment see (Poznic, 2014) [↑](#footnote-ref-2)
3. It should be taken as an open question whether these convergences indeed produce value-changes, which is not the same as amplifying existing value conflicts and struggles between different stakeholders. [↑](#footnote-ref-3)
4. The list is that of other traditionally conceived transformative technologies. Naturally, nanotechnology, as well as the other NBIC technologies, can converge with traditional technologies such as conventional weapons systems. [↑](#footnote-ref-4)
5. Discussions of utopia/dystopia should be taken as culturally desirable/undesirable futures rather than taken as a universalism (often Western conception of desirability). [↑](#footnote-ref-5)
6. The financial support for nanotechnology in the US and many other Western countries has been in decline in recent years. It should be made clear that the hype and the financial investments this entailed is over now. However, the absolute value of the investment is high enough to warrant consideration nonetheless. [↑](#footnote-ref-6)
7. See Davis and Nathan (2015) for a further discussion of moral universality and ethical commitments. [↑](#footnote-ref-7)
8. For further analysis on stakeholder participation, co-creation processes, and moral assessment regarding nanotechnology, in particular, please see Krabbenborg 2012; Brey 2012; Rip 2009; Boenink 2010, 2009; Van Lente et al. 2012; and Islam and Miyazaki 2009. [↑](#footnote-ref-8)