Design for Sustainable Development: A Framework for Sustainable Product Development and its Application to Earthmoving Equipment

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Abstract

Innovation to improve the eco-efficiency of products and services is often thought to take place at four levels: product improvement, product redesign, function innovation and system innovation. This paper presents a framework, Design for Sustainable Development (DfSD), to help organise action for product and service innovation within and between the lower three levels. At the highest level (function innovation), the graphical scenario-building technique Scenario Network Mapping is used to explore and chart possible future developments for the current market of the product or service. The scenarios take a long-term (20 year) perspective and are constructed through dialogue with key stakeholders. New product/service concepts can then be 'tested' against these scenarios for robustness (i.e., performance under multiple scenarios) and adaptability. Once a concept is selected, product and technology roadmaps are drawn up to plan the development of the product/service and the different social and environmental benchmarks that should be met generation-by-generation. At the lower levels (product improvement and product redesign), techniques such as life cycle assessment, eco-design and material blacklists are used to help optimise the current product/service offering and comply with relevant legislation. The framework is illustrated by a case study focusing on the use of wheeled loaders in the construction aggregates industry up to the year 2030.

1 Introduction

> The transition to a sustainable society will challenge the capacity of countries everywhere to change and adapt. Some adjustments will occur in response to economic forces, some in response to public policy changes, and still others as a result of voluntary changes in life-styles. (L. Brown, 1981, p. 284)

Lester Brown's words seem fitting for this conference, *Transitions to Sustainability*, despite the fact that nearly thirty years have passed since they were written. However, it was not until some years later that sustainable development started to gain widespread recognition. Its popularity in the late 1980s and 1990s was partly due to *Our Common Future*, the influential report that defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 43), and also the United Nations Conference on Environment and Development that followed in 1992. Since then sustainable development has been adopted as a guiding principle of organisations and governments throughout the world (Kates et al., 2005). Yet, despite widespread acceptance of the WCED (Brundtland) definition as a general definition, the question of how to translate sustainable development into practice remains at the centre of ongoing debate (Kates et al., 2005) and human development remains far from sustainable (e.g., UNEP, 2007).

This paper presents a framework, Design for Sustainable Development (DfSD), which assists firms to significantly improve the environmental and social performance of their products and services through a series of incremental, but far-sighted, steps. Its application is illustrated by a case study of wheeled front-end loaders for the construction aggregates industry. As the DfSD framework requires long-term innovation, this paper first presents brief reviews of the literature on innovation, sustainable product/service design and futures studies.

2 Innovation for Sustainable Development

Innovation that produces novelty – be it a new technology, a new product/service, a new process or new knowledge – may be driven by a perceived need ('market-pull'), or, once an innovation emerges, a use for it can be sought ('science/technology-push') (e.g., Mansfield and Wagner, 1975, p. 183). This distinction between supply- and demand-side factors is, however, somewhat artificial (e.g., Nelson and Winter, 1977; Dosi, 1982). Both the supply of novelty and the need for it co-evolve (Rip and Kemp, 1998). To use a crude example, a person cannot need a faster personal computer unless they already have a relatively slow one.

In this evolutionary view of technological change, it is therefore helpful to think of 'society' and 'technology' as two interdependent parts of a 'socio-technical system' (e.g., Rip and Kemp, 1998). A socio-technical system can be divided into any number of levels. However, various authors (e.g., Rip and Kemp, 1998; Kemp et al., 2001; Geels, 2002) choose three: niches, regimes and landscape. A niche is a protected pocket of innovation, a regime is a dominant combination of technologies and social practices (e.g., the personal motorcar regime), and the landscape is the set of long-term trends and practices by which society is structured, both in a physical sense (e.g., the layout of cities) and in a social sense (e.g., in the need for personal mobility) (Rip and Kemp, 1998). The interactions between the levels are illustrated below in Figure 1.

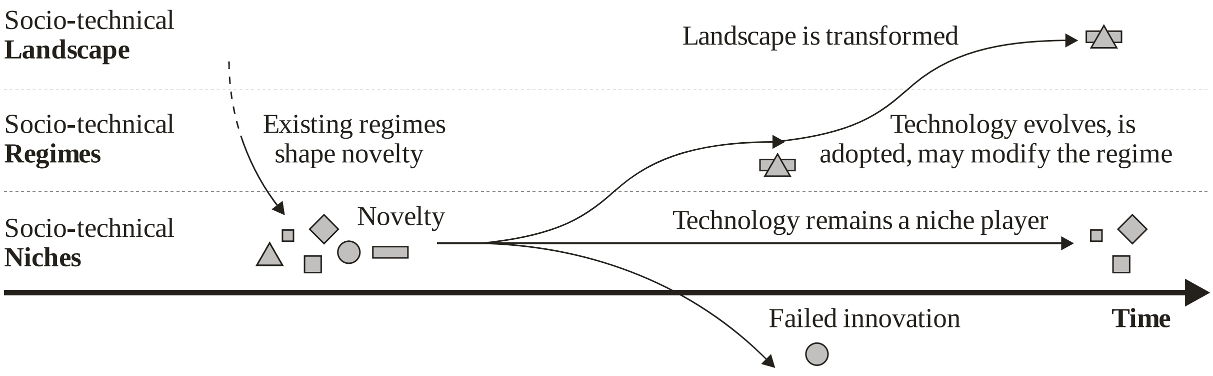


Figure 1: Socio-technical change through novelty creation and adoption (adapted from Rip and Kemp, 1998; Kemp et al., 2001; Geels, 2002)

Each level is constantly changing as new innovations are trialled and either adopted or discarded. At the regime level, innovation is incremental as it aims to improve upon an existing set of structures and maintain a kind of dynamic stability (Geels, 2002, p. 1260). Niche innovations, in contrast, may be radical and therefore may not align with the existing regimes (Schot, 1998; Geels, 2002, pp. 1260-1261). They may also be uncompetitive, at least initially, as they have received relatively little investment, there have been few opportunities to understand their strengths and weaknesses, and they do not benefit from economies of scale

(Rip and Kemp, 1998, p. 328). Yet both can exist concurrently because niches occupy domains within society protected by conditions that do not apply to the dominant regimes, e.g., government subsidies. The conditions that support the niche are therefore necessary for its continued survival and further development as well as learning and relationship-building among niche actors (Rip and Kemp, 1998). If this supportive environment ceases to exist, the niche must either collapse or be adopted by a regime, in which case it must be sufficiently well developed to be perceived as useful by the regime (Nelson and Winter, 1977, p. 62).

3 Sustainable Product/Service Design

Rapid growth of the global human population over the past few centuries has dramatically increased the scale of the world’s economies. This has both led to and been supported by ever-increasing flows of products and services, each of which has an impact upon the natural environment due to the materials and/or energy it requires. In order to assess and reduce these impacts, a significant body of research has developed over the last two decades under various names, e.g., life cycle assessment (LCA), eco-design, Design for Environment (DfE), Design for Sustainability (DfS or D4S) and sustainable product design/development.

As a design progresses from an abstract idea to a concrete product or service, its costs and its impacts become increasingly locked in (Lewis and Gertsakis, 2001, pp. 13-15). In order to make large improvements in economic and environmental performance, it is therefore necessary to reverse the design process, i.e. to move from the concrete to the abstract, and to conceptualise new ways of meeting the needs fulfilled by the current product/service.

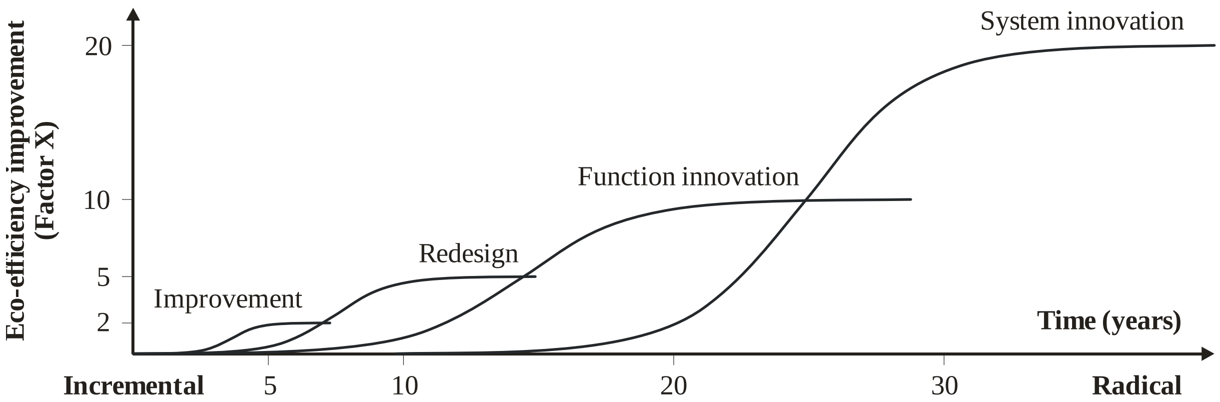


Figure 2: Four levels of eco-efficiency improvement (adapted from Brezet, 1997)

Eco-efficiency, a ratio of economic value or cost to environmental impact or improvement (Huppes and Ishikawa, 2005), is a common benchmark to assess the relative performance of a set of concepts. The scope for improving eco-efficiency depends upon the degrees of freedom available for innovation (Brezet, 1997) and is therefore relatively low for an existing product, which has a defined form and function, and relatively high for improving the provision of a social need. This is illustrated above in Figure 2. As an example, to reduce the emissions of a car, a designer could add a catalytic converter (product improvement), redesign the engine to be more fuel efficient (product redesign), design and promote lightweight two-person cars as a more efficient means of urban commuting (function innovation), or participate in the design and/or implementation of a flexible mass transit system as an alternative means of mobility (system innovation). As higher levels of eco-efficiency may require more significant behavioural change, these innovations are likely to take longer to diffuse within society, hence the staggering of each strategy along the x-axis.

4 Future Scenarios for Opportunity and Threat Identification

As radical innovations may take decades to diffuse within society (Figure 2), and as there are many possible ways in which they may be adopted and used, it is difficult to make single-point forecasts with any accuracy. One approach to manage this uncertainty is to explore multiple possible futures. Decisions can then be assessed based upon their performance in the various scenario worlds.

There are many ways in which scenarios can be constructed (e.g., Bishop et al., 2007). A common approach, popularised initially by Schwartz (1991), and referred to as 'critical uncertainties' by van der Heijden et al. (2002) and the 'GBN matrix' by Bishop et al. (2007), maps out driving forces in two-dimensional space: one axis represents the degree of certainty and the other represents the degree of importance to the entity's future. Unimportant drivers can safely be ignored, drivers that are both relatively certain and critical are 'predetermined elements' and become the baseline for all scenarios, and drivers that are both critical and uncertain define the differences between scenarios. The number of scenarios depends upon the number of critical uncertainties. With two critical uncertainties there would be a maximum of four scenarios (low A + low B; low A + high B; high A + low B; high A + high B), three uncertainties yields nine scenarios, four yields 16, and so on. In practice, there may be fewer scenarios as certain combinations of the critical uncertainties may be considered implausible or sufficiently similar by the scenario builders.

There are several problems with this approach. Firstly, the scenarios are often presented in a way (e.g., squares in a two-by-two matrix with self-contained storylines) that makes them appear mutually exclusive, yet they often play out together (Liebl, 2002, p. 175). This is to be expected because, even if the scenarios are mutually exclusive for a single entity or a single action, multiple combinations may occur when multiple entities and/or actions are considered. For example, Randall (1997) presents four scenarios for the Internet in 2000, the themes of which are: (1) interaction, entertainment and community; (2) information repository; (3) electronic commerce; and (4) an unstructured frontier. While these scenarios were never intended to be mutually exclusive (p. 159), the Internet of today is made up of elements from each scenario, for example: (1) media streaming and social networking websites; (2) online journal databases; (3) online auctioneers and retail giants; and (4) peer-to-peer file sharing. This is problematic because all of the indicators (drivers) of change Randall (1997) identified, except some from his frontier scenario, played out at a similar time. From the perspective of the scenarios' users, it would have been difficult to identify which one was occurring.

Secondly, the scenarios focus on the extremes of each critical uncertainty. It is unlikely that such extremes will occur in practice; what is more likely is a novel combination between various drivers of change (Liebl, 2002, p. 175).

Thirdly, the scenarios are often presented as a snapshot of a possible future state. While this can lead to compelling narratives and stimulate creative thinking, the steps required to reach each scenario are often underemphasised. To create a roadmap, however, you need to know how to get from A to B. Furthermore, a compelling narrative can be hard to 'unlearn' (Liebl, 2002, p. 175) and yet unlearning is crucial because much of the power from scenarios comes from their ability to stimulate a strategic conversation (van der Heijden, 2005) and such a conversation must develop over time as new information becomes available.

An alternative approach, Scenario Network Mapping (List, 2005), explicitly reveals the underlying logic of the scenarios by presenting them as chains of cause-and-effect links. Each event may have multiple causes and may be a cause of multiple future events. For an example of a scenario network map, please see Figure 4 on page 7.

5 The Design for Sustainable Development (DfSD) Framework

As each level of innovation presented in Figure 2 has a different time horizon and a different scope, they can be tackled at different levels within an organisation. In the context of a firm, improvement and redesign of existing products and services are tasks already performed by product development teams and practitioners. On the other hand, function and system innovation are inherently strategic as they require a long-term perspective and define the firm's future portfolio of products and services.

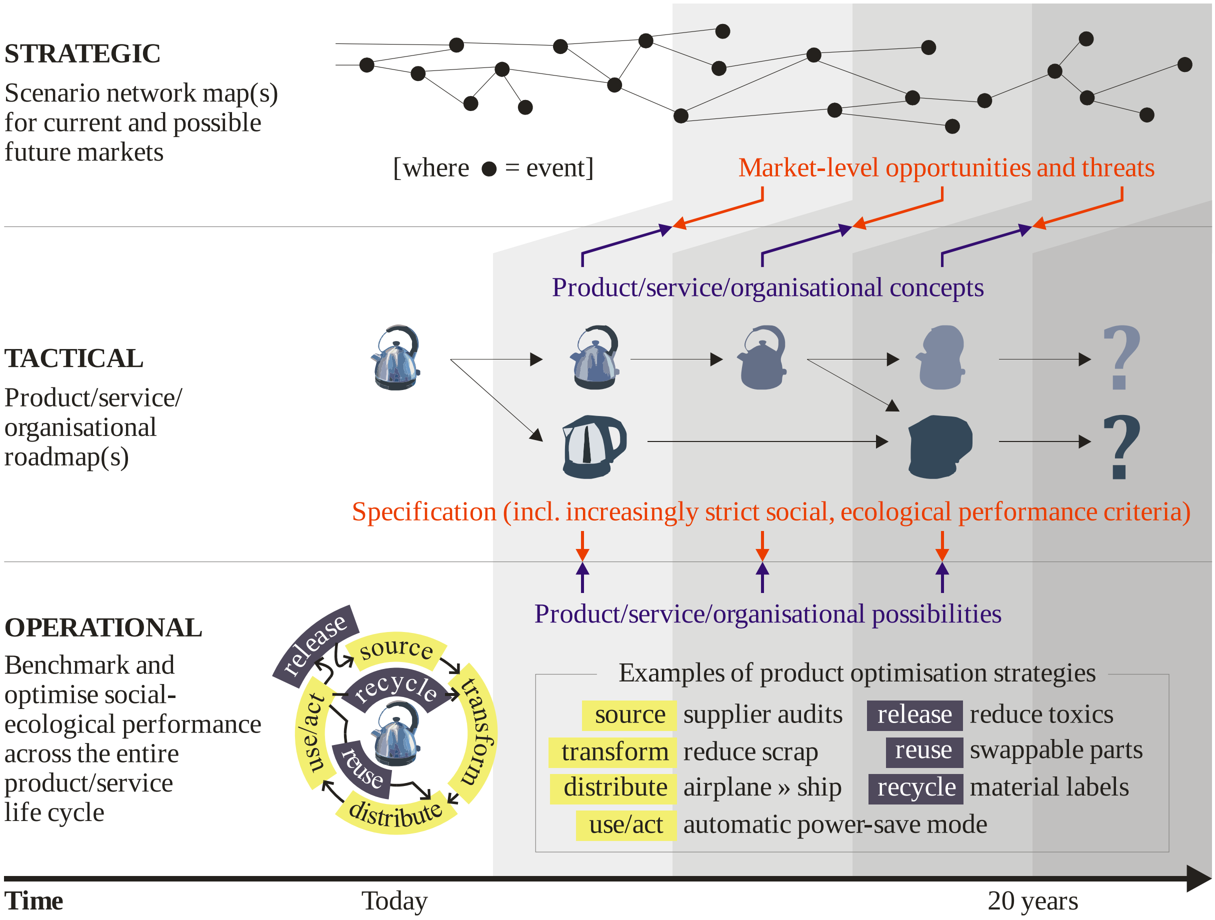


Figure 3: Design for Sustainable Development (DfSD) Framework

The framework presented in Figure 3, Design for Sustainable Development (DfSD), provides a methodology for firms to manage innovation aimed at improving the social and ecological performance of their products and services. The starting point is to strip a product or service back to the functions it performs for its users or society at large. The next step is to identify one or more existing or potential market for this feature set. With the function(s) and market(s) in mind, questions regarding the future should be developed as "the futures of *[specified activity or concept]* among *[specified social group]* in *[specified location]* during *[specified time range]*" (List, 2005, p. 209, original emphasis).

In this case, the time horizon chosen is 20 years. While this number is somewhat arbitrary, it has been selected for several reasons:

1. It is sufficient time for function innovation (see Figure 2);
2. In most cases a product will undergo several major redesigns over a 20 year period, therefore potential future improvements can be mapped and phased in over time;

3. Given long diffusion times (often decades) for many radical technologies, it is likely that the seeds of change will be visible now;
4. It is the approximately the length of one human generation and therefore allows a firm to consider intergenerational equity, a crucial concept for sustainable development (WCED, 1987).

The next step is to assemble a team and construct the scenario network maps (strategic level). The team must be a diverse group, each member of which has a stake in the future under study (List, 2005, ch. 5). The maps are typically created through a series of four workshops, though the format can vary (List, 2005, appendix 5). Once the scenarios have been created, different design concepts can be tested against them for robustness, a measure of the relative performance of each concept across the set of scenarios (Lempert, 2002, p. 7310). This robustness may be inherent to the concept or, alternatively, it may because the concept is easy to adapt to a range of circumstances (Lempert, 2002, p. 7310). (An alternative approach is to design a product or service that is expected to be a niche player. However, this strategy is inherently riskier as the chosen niche may not come into being as anticipated.) Once one or more concepts have been selected, roadmaps which chart their development over time can then be prepared. The use of networked scenarios and the separation of the market level from the product and technology levels mean that DfSD is compatible with popular roadmapping approaches, e.g. the T-Plan approach of Phaal et al. (2001a, 2001b). These roadmaps make it possible to phase in increasingly stringent social and environmental performance criteria over time while still ensuring that the product/service is developing in a way that is compatible with the firm’s longer-term goals. For example, generation B might be required to have 10% lower energy consumption than generation A.

The change in shading between the strategic and the tactical/operational levels highlights that a new product/service must be developed in anticipation of a future (or ongoing) market need. The length of time between conceptual development and production/implementation varies from industry to industry, e.g., the time allowed for new product development might be less than a year for a consumer electronic product but several years for an industrial product.

At an operational level, techniques to improve social and environmental performance, such as life cycle assessment and eco-design, can be applied at the various stages of the product /service life cycle. Detailed lists of techniques have been omitted as toolboxes for sustainable product design are widely available (e.g., Brezet and van Hemel, 1997; Lewis and Gertsakis, 2001; Robèrt et al., 2002; Wrisberg et al., 2002; Waage et al., 2005; Crul et al., 2009).

6 Case Study: Wheel Loaders for Construction Aggregates up to 2030

The product for this case study is the wheeled front-end loader, specifically wheeled loaders used in the construction aggregates industry in the industrialised world. As Scenario Network Mapping is intended for localised use so that all relevant stakeholders can be brought into the same room (List, 2005, appendix 5), the authors have modified the process so that it can be applied on a regional or global scale. In particular, the sessions from workshops 1 and 2 (List, 2005, appendix 5) were formulated as questions for phone interviews with key stakeholders, such as equipment manufacturers and aggregates producers. The remaining two workshops were condensed into one half-day session, which involved 19 people, mostly from Actronic Ltd., the company sponsoring this research. The next two sections present some preliminary outcomes from the phone interviews, workshop and desk research. The market level (construction aggregates) will be discussed first, followed by the product level.

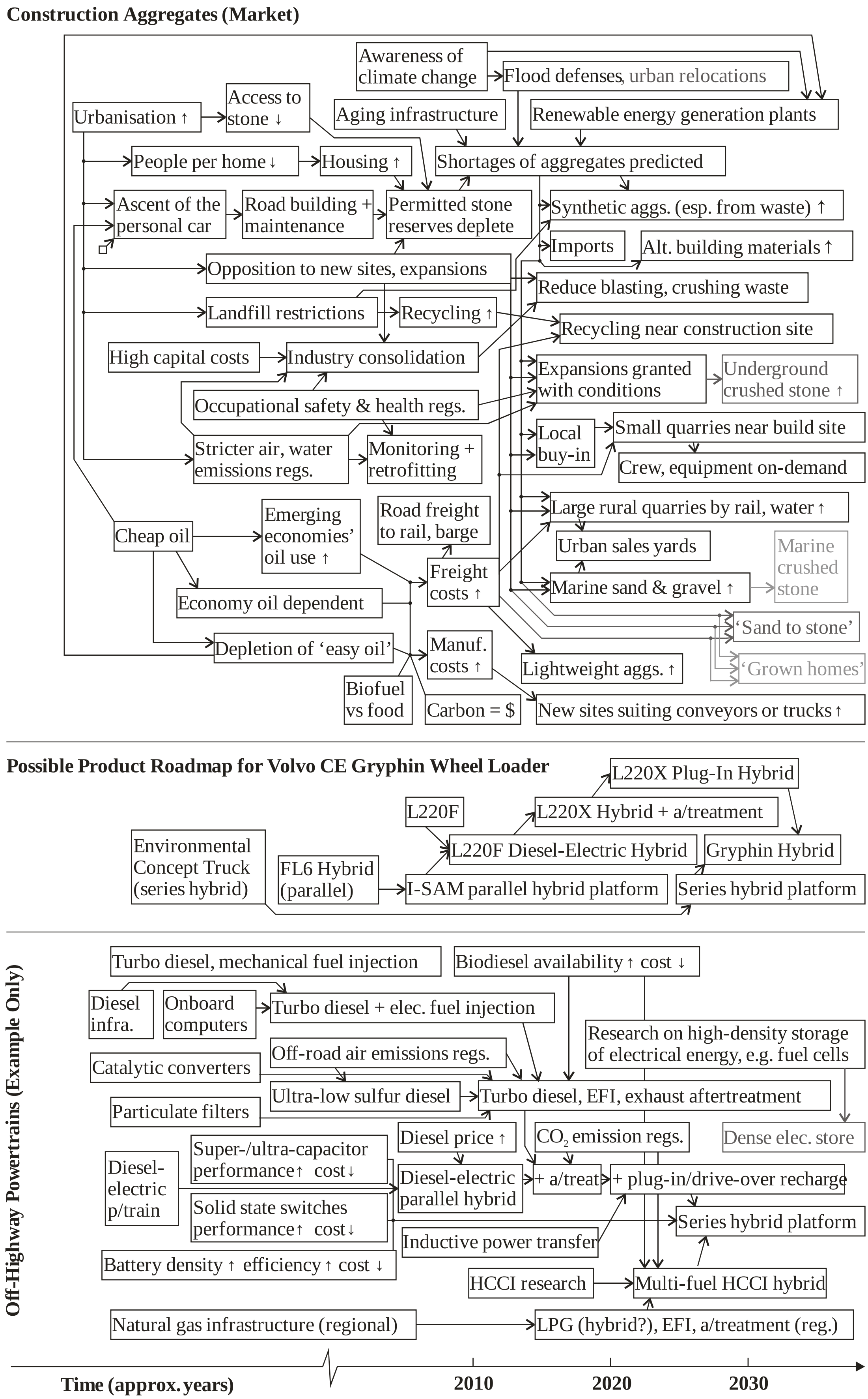


Figure 4: Future scenarios for construction aggregates in the industrialised world and a possible roadmap for the Gryhpin wheel loader and its powertrain

6.1 Market-level: Scenarios for the (construction) aggregates industry

Aggregates are granular materials that are suitable for use on their own or in a conglomerate with a binder, such as cement, lime or bitumen (Alexander and Mindess, 2005, p. 2; T. Brown et al., 2007, p. 1). Figure 5 below illustrates the sources and uses of aggregates in the USA in 2003. As can be seen, aggregates may be natural (i.e. from crushed stone or sand and gravel quarries), recycled (e.g. demolition waste) or synthetic/manufactured (e.g. furnace slag and fly/fuel ash). Typical uses of construction aggregates include concrete, asphalt, road bases, drainage, fill, railway ballast and shoreline armour rock (rip rap) for erosion control. Based on the US data, the bulk of natural aggregates are used in concrete (31%), road bases and coverings (26%), bituminous concrete (13%), fill (12%) and cement manufacture (5%). This means that the future of the industry is heavily dependent on the future of the construction sector. As emerging economies like China and India have much larger construction growth rates than industrialised countries, the Scenario Network Map in Figure 4 on page 7 focuses on industrialised countries only.

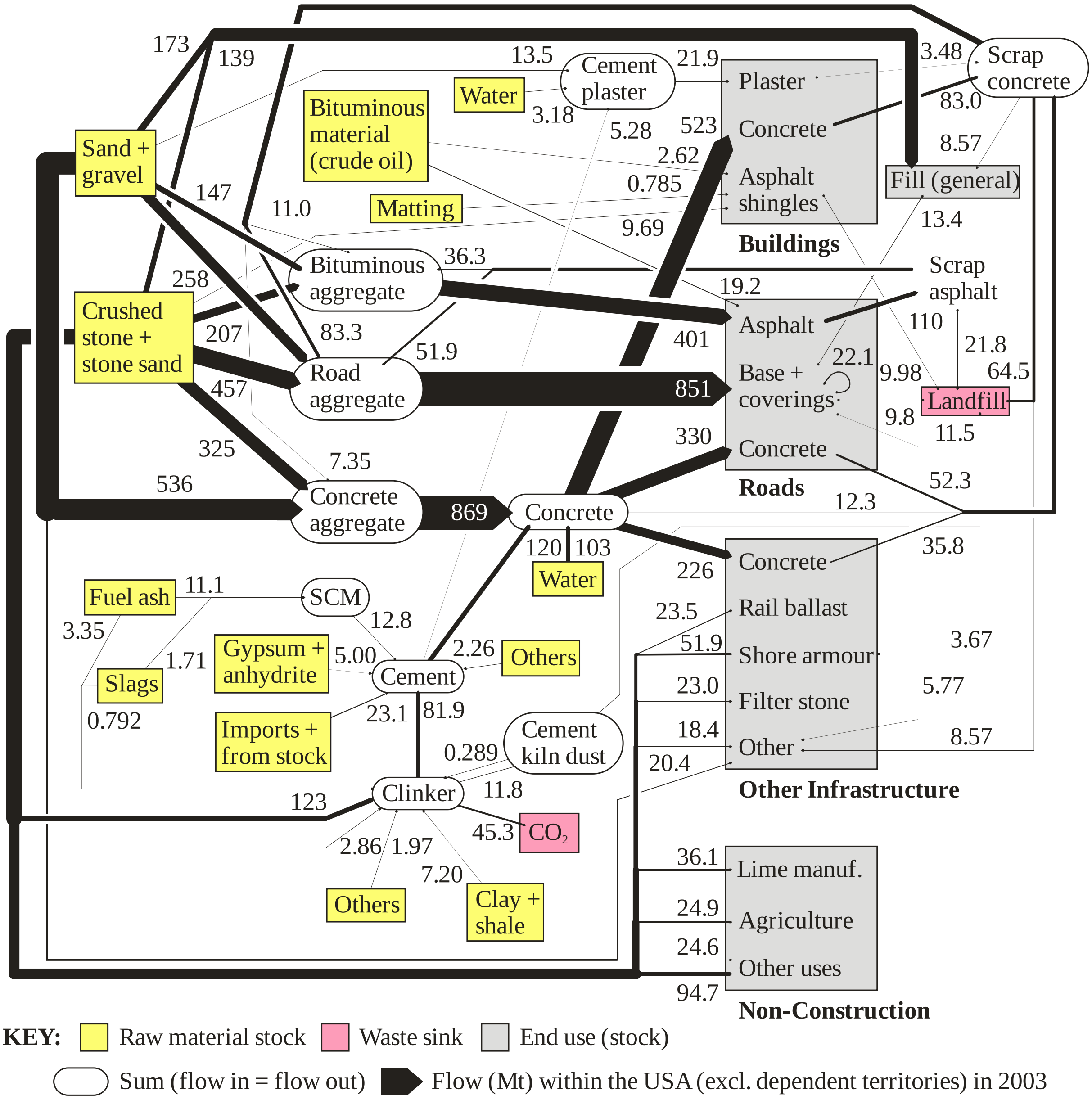


Figure 5: Material flow analysis for construction aggregates, cement, concrete and asphalt concrete in the USA in 2003. Excludes materials for energy generation. All flows in million tonnes. (See Appendix A)

Construction aggregates are high-volume, low-value products (T. Brown et al., 2007). Natural aggregates are mined in a similar way to industrial minerals, typically using open cast surface mining (see Figure 6). However, unlike most minerals, their desirable quality is their bulk, which means they cannot be purified to reduce their mass or volume, making distribution a significant cost. The cost of transport by truck over 30-50 km can equal the cost of the aggregate itself (Wilson, 2007). New quarries are therefore either positioned near areas where there is expected to be significant demand for construction, e.g. near growing towns/cities, or near navigable waterways and/or railways so that the freight cost per unit distance can be reduced. However, as few job sites will be connected to the same railway or waterway as the producer, in many cases the final leg must be done by truck. In 2005, truck freight accounted for 90% of all transport for natural construction aggregates in the UK (T. Brown et al., 2007) and 92% in the USA (authors' compilation of data from Bolen, 2007; Willett, 2007).

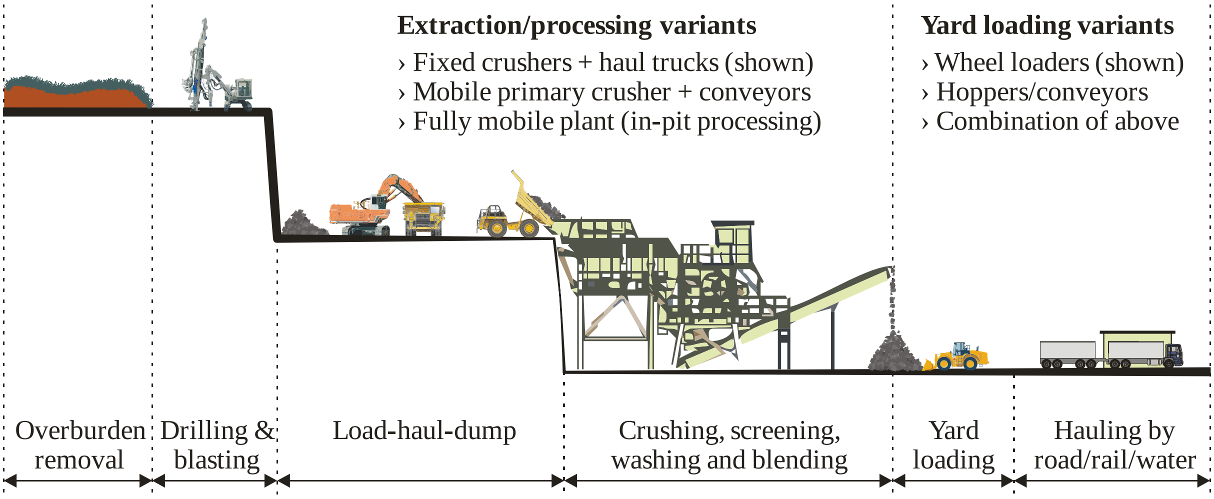


Figure 6: Unit operations in a typical crushed stone quarry

Furthermore, the need to position new sites near growing communities (due to high transport costs) can lock the quarry into a vicious cycle where increasing urbanisation increases sales but also decreases the quarry's ability to access new reserves, either because additional land is not available or because of public opposition (e.g., Kelly, 1998, p. 2). Opposition to new sites from local residents is often informally labelled as 'not in my back yard' (NIMBY) and may be due to a number of factors, including noise, dust, vibrations and potential fly-rock from blasting, the volume of large trucks entering/exiting the site, fundamental alterations to the landscape from surface mining, and disruption of other species' habitats. A selection of dynamics that often occur between a quarry and its surrounding community are given in Figure 7.

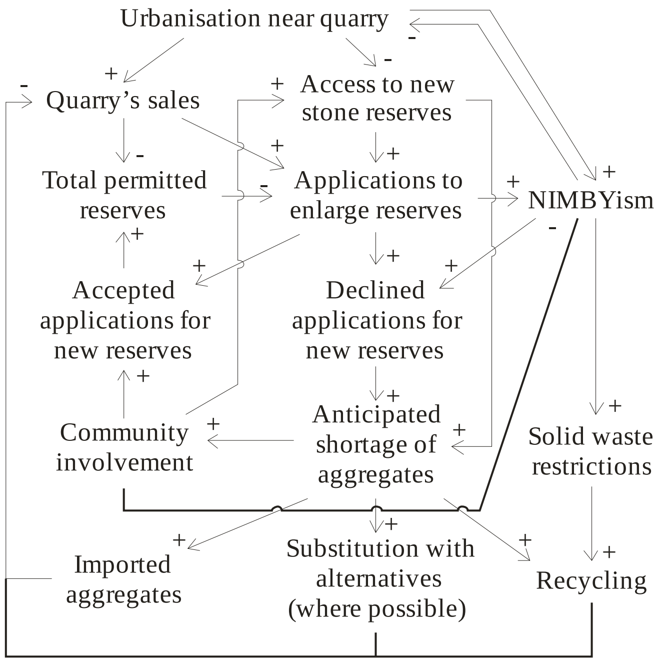


Figure 7: Causal loop diagram showing the interactions between the quarry and its surrounding community

Reserves of natural stone are extremely large in many countries, to the point where they are often stated to be practically unlimited (e.g. Cammarota, 1992, p. 74). However, both the distribution of reserves and the ability to access them vary considerably. In the short term this means that quarries will attempt to extend their existing reserves as long as possible. Longer term, quarries may need to either relocate to rural areas that are near to waterways or rail, or, alternatively, actively engage the public and thereby reduce NIMBYism (see Figure 7). Given high freight costs, another, and perhaps the most radical, change would be not to buy aggregates in the first place, but rather to produce them on-site. Two examples include ‘grown homes’ where plants are grown on-site in such a way that they form structures (Joachim, 2010) and also the use of micro-organisms to alter the composition of soils, e.g. the use of the *Bacillus pasteurii* to create cemented sand (DeJong et al., 2006). As the ‘grown homes’ idea is the least well developed of the two, and has potentially high social barriers to overcome, it is placed outside of the 2030 horizon in light grey.

6.2 Product-level: Gryphin concept wheel loader by Volvo

The product chosen for analysis is Gryphin, a concept wheeled loader for the 2020s designed in 2006/7 by Volvo Construction Equipment (‘Volvo CE’). This concept was selected for two reasons: (1) wheel loaders are common in quarries and sand and gravel plants; and (2) there is sufficient information in the public domain to allow a roadmap for Gryphin to be constructed (see Figure 4). As a concept vehicle, Gryhpin may never be fully realised; however, this roadmap is drawn as if it will be. It is intended to depict one set of possible development paths for illustrative purposes only. It is in no way linked to or endorsed by the Volvo Group.

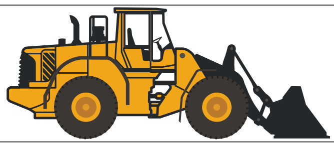
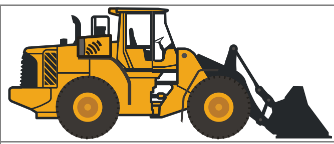
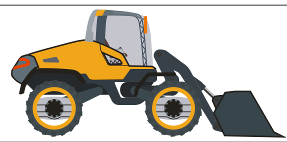
Gryphin’s conceptual design (Volvo CE, 2007a) features:

- High visibility from the cab using all-round smart glazing, which heats up to prevent frost and darkens in direct sunlight to prevent glare, and see-through structural pillars;
- A middle- (rather than front-) mounted boom to reduce torsional stresses and increase front visibility;
- Electric motors in each wheel to replace the driveline, decreasing weight, increasing ground clearance, improving traction control and allowing regenerative breaking;
- Intelligent independent suspension to each wheel providing a smoother ride over rough terrain and allowing the loader’s frame to be lowered for high-speed travel and raised for increased dumping height;
- Electric hybrid engine, replaced by fuel cells when they become commercially viable, which improves fuel economy, reduces emissions and decreases engine bay size;
- High stability as electrical cables allow components of the powertrain (e.g. electric motors) to be positioned for stability, rather than mechanical connections;
- Extendable counter-weight at the rear of the loader provides greater reach; and
- Multi-function joysticks in the cab replace the steering wheel and levers.

Figure 4 consists of three levels: the market level, the product level and the technology level. In order to display the map on a single page, only the roadmap for powertrain technology is presented. A full roadmap would also consider the chassis, hydraulics, suspension, etc.

Volvo CE unveiled its first step towards Gryphin in 2008: the prototype L220F Hybrid Wheel Loader. It has all the features of Volvo CE’s existing L220F loader: articulated steering, load-sensing hydraulics for the boom/bucket, a turbo-charged diesel engine with electronic fuel injection, exhaust gas recirculation and air-to-air cooling, an automatic transmission, wet disc brakes, and a range of safety, maintenance and operator comfort features (Volvo CE, 2007b). The major change is the addition of Volvo Group's I-SAM (Integrated Starter Alternator Motor) hybrid powertrain (Volvo CE, 2007a). This supplements the diesel engine with an electric motor that: (1) is used at start-up and at low speeds instead of the diesel engine, as this is the point where the engine is least efficient; (2) acts as an alternator to provide electricity to the air conditioning, lights and other electrics, allowing the engine to be switched off when it would normally need to idle; and (3) provides a power boost to the engine (Volvo CE, 2007a). The I-SAM is run directly by the engine or from a battery pack that is recharged either by the engine when it is operating at a point of high efficiency, or when the loader brakes (i.e. the electric motor acts as a generator) (Volvo CE, 2007a). The specifications of the L220F, L220F Hybrid and Gryphin are given below in Table 1.

Table 1: Brief specifications for Volvo Construction Equipment's L220 wheel loaders (estimates in grey)

			
Model	L220F	L220F Hybrid	L220X (Gryphin)
Launch	2007	2012	2025
Hybrid Type	None	Parallel	Series
Transmission	Automatic (mechanical)	Automatic (mechanical)	Electric
Gross motor power (kW)			
Diesel	261	261	200
Electric	--	50	250
Hybrid. factor	0%	16%*	56%**
Peak motor torque (Nm)			
Diesel	1756	1756	1400
Electric	--	700	1800
* Hybridisation factor = $P_{EM} / (P_{EM} + P_{ICE})$ (Lukic and Emadi, 2004)			
** For a series hybrid, the electric motor is the sole source of propulsion			

Hybrid vehicles are defined as vehicles that can utilise two or more energy sources for propulsion (Emadi et al., 2005, p. 763). They can be broadly classified as series, parallel, or some combination thereof (Chan, 2007). As I-SAM-equipped vehicles can be driven by the diesel engine, the electric motor, or both together, they can be classified as parallel hybrid vehicles. A series hybrid is driven only by the electric motor; all other energy sources (e.g., diesel engine and battery) provide power to this motor. A parallel hybrid has the advantages that it requires a relatively small electric motor and battery pack and needs only two propulsion devices (internal combustion engine and electric motor), whereas a series hybrid requires three (ICE, electric motor and generator), making its implementation potentially more expensive and also decreasing efficiency due to the additional conversion steps (Chan, 2007, p. 708). The series hybrid has the advantage that it can always run the ICE near the point of maximum efficiency; however, Katrasnik et al. (2007) have shown that, for their test equipment, the losses due to the energy conversion steps in the series hybrid make it less efficient that the parallel hybrid under most driving conditions. Volvo Group experimented with a series gas-electric hybrid Environmental Concept Truck in the early 1990s (Volvo Trucks, 2010). Perhaps it is telling that their next experiment was a diesel-electric parallel hybrid FL6 truck in the late 1990s (Volvo Trucks, 2010). In order to implement the Gryphin's series hybrid powertrain, Figure 4 requires improved battery charge-discharge efficiency and improved solid state switching performance, together with lower cost.

Of the market level trends which are important to the future of the wheeled loader, changes in market composition are most relevant. Many of the 'end points' in Figure 4 are favourable for wheeled loaders. Construction aggregate recycling typically requires a wheeled loader or excavator to lift rubble into trucks (off-site recycling) or crushers (on-site recycling). The size of construction project would determine whether a relatively large loader like an L220 would be needed. Expansions of existing quarries and the creation of small quarries with mobile on-demand crews favours current quarry layouts where wheeled loaders are commonly used to load trucks in the yard and may also be used to load haul trucks at the blast face. The biggest risks identified are posed by marine sand and gravel, which uses dredges, and super quarries, which may make greater use of front shovels and excavators for heavy digging and conveyor systems to load trains or barges. Wheeled loaders are still likely to feature, however, perhaps in (un)loading trains/barges and perhaps in urban sales yards. Wheeled loaders can therefore be considered quite a robust technology for construction aggregates over the next 20 years, though the development of land-based super quarries and marine sand and gravel should be watched. Using the L220F as a baseline, and considering fuel as an example, fuel economy targets could be defined as: 10% by 2008 (current estimate for the L220F Hybrid); 20% by 2020 (L220X Plug-In Hybrid) and 30% by 2025 (Gryphin Hybrid).

7 Discussion and Further Work

This paper presents a framework for sustainable product development, Design for Sustainable Development (DfSD), which assists product/service developers to chart the future of their products/services and then to set increasingly strict environmental and social performance criteria that can be phased in generation-by-generation. The rationale for such an approach is to ensure that a firm is designing the 'right' product/service before focusing development effort to optimise it. This is part of an ongoing study being conducted by the authors into the future of earthmoving equipment in the construction aggregates industry for the 20 years to 2030. The full results of this study will be published in the near future.

8 Acknowledgements

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Appendix A

	A	B	C	D	E
1	**MATERIAL FLOW ANALYSIS FOR CONSTRUCTION MATERIALS IN THE U.S.A. IN 2003**				
2	Limited to selected construction materials in the continental USA for the 2003 calendar year.				
3	Excludes minor flows and materials for energy generation. All masses in million metric tonnes (Mt).				
4	Data, particularly waste and recycling, are approximate and valid to no more than 3 significant digits.				
5					
6	**Exiting**	**Entering**	**Flow**	**Formula**	*****
7	Asphalt	Roads, bitumen	421	=C11+C10	
8	Asphalt shingles	Buildings, as. shingles	11.6	='R'!C29	
9	Asphalt shingles	Landfill	1.45	='R'!C28	
10	Bituminous aggregate	Asphalt	401	='R'!D3+C68+C71	
11	Bituminous material	Asphalt	19.2	=(('R'!D3+C71)/0.95)*0.05	
12	Bituminous material	Asphalt shingles	2.62	='R'!C22	
13	Buildings, as. shingles	Landfill	8.53	='R'!D28	
14	Buildings, concrete	Scrap concrete	83	=350*0.9072*0.55*C28/(C22+C28+C29+C30)	**1**
15	Buildings, plaster	Scrap concrete	3.48	=350*0.9072*0.55*C22/(C22+C28+C29+C30)	**1**
16	Cement	Cement plaster	5.28	='C'!D52	
17	Cement	Concrete	120	='C'!D51	
18	Cement, other	Cement	2.26	='R'!C56-'R'!C54	
19	Cement imports, stock	Cement	23.1	='R'!B63+'R'!B66+'R'!B68-'R'!B67	
20	Cement kiln dust	Clinker	0.289	='R'!B51	**2**
21	Cement kiln dust	Landfill	11.5	=C25-C20	
22	Cement plaster	Buildings, plaster	21.9	='C'!E52	
23	Clay & shale	Clinker	7.2	='R'!B49	
24	Clinker	Carbon dioxide	45.3	=0.553*'R'!B39	**3**
25	Clinker	Cement kiln dust	11.8	='R'!B56-C26-C24	
26	Clinker	Cement	81.9	='R'!B39	
27	Clinker, other	Clinker	1.97	='R'!B55	
28	Concrete	Buildings, concrete	523	=('C'!B13/('C'!B13+'C'!D13))*SUM('C'!I38:I40) +('C'!B14/'C'!E14)*'C'!I48+'C'!I49	
29	Concrete	Other infrastructure	226	=('C'!D13/('C'!B13+'C'!D13))*SUM('C'!I38:I40) +('C'!D14/'C'!E14)*'C'!I48+'C'!I50	
30	Concrete	Roads, concrete	330	='C'!I41	
31	Concrete	Scrap concrete	12.3	='C'!H53	
32	Concrete aggregate	Concrete	869	='C'!F51	
33	Crude oil	Bituminous material	21.8	=C11+C12	
34	Crushed stone, sand	Agriculture	24.9	='R'!B15	
35	Crushed stone, sand	Asphalt shingles	9.69	='R'!C23+'R'!C24+'R'!C26	
36	Crushed stone, sand	Bituminous aggregate	207	='R'!B3	
37	Crushed stone, sand	Clinker	123	='R'!B48	
38	Crushed stone, sand	Concrete aggregate	325	='R'!B2	
39	Crushed stone, sand	Fill	139	='R'!B8	
40	Crushed stone, sand	Filter stone	23	='R'!B11	
41	Crushed stone, sand	Lime manufacture	36.1	='R'!B14	
42	Crushed stone, sand	Other, construction	18.4	='R'!B12	
43	Crushed stone, sand	Other, non-construct.	94.7	='R'!B16	
44	Crushed stone, sand	Rail ballast	23.5	='R'!B10	
45	Crushed stone, sand	Road aggregate	457	='R'!B4	
46	Crushed stone, sand	Shore armour	51.9	='R'!B9	
47	Fuel ash	Clinker	3.35	='R'!B52	
48	Fuel ash	SCM	11.1	='R'!B34	
49	Gypsum & anhydrite	Cement	5	='R'!D54	
50	Matting	Asphalt shingles	0.785	='R'!C25	
51	Other infrastructure	Scrap concrete	35.8	=350*0.9072*0.55*C29/(C22+C28+C29+C30)	**1**
52	Road aggregate	Roads, base, cover	851	=D102	
53	Roads, base, cover	Fill	13.4	=0.262*(C57+C58)*(C45+C66)/(C30+C7)*0.33	**4**

Appendix A

	A	B	C	D	E
54	Roads, base, cover	Landfill	9.8	=0.192*(C57+C58)*(C45+C66)/(C30+C7)*0.33	**4**
55	Roads, base, cover	Other, construction	5.77	=(C57+C58)*(C45+C66)/(C30+C7)*0.33-C53-C54-C56	**4**
56	Roads, base, cover	Roads, base, cover	22.1	=0.433*(C57+C58)*(C45+C66)/(C30+C7)*0.33	**4**
57	Roads, bitumen	Scrap asphalt	110	110	**5**
58	Roads, concrete	Scrap concrete	52.3	=350*0.9072*0.55*C30/(C22+C28+C29+C30)	**1**
59	Sand & gravel	Bituminous aggregate	147	='R'!C3	
60	Sand & gravel	Clinker	2.86	='R'!B50	
61	Sand & gravel	Cement plaster	13.5	='C'!F52	
62	Sand & gravel	Concrete aggregate	536	='R'!C2+'R'!C6+('R'!C5-'C'!F52)	
63	Sand & gravel	Fill	173	='R'!C8	
64	Sand & gravel	Other, construction	20.4	='R'!C12	
65	Sand & gravel	Other, non-construct.	24.6	='R'!C16	
66	Sand & gravel	Road aggregate	258	='R'!C4	
67	SCM	Cement	12.8	='R'!D34	
68	Scrap asphalt	Bituminous aggregate	36.3	=C57*0.33	**6**
69	Scrap asphalt	Landfill	21.8	=(1-73/91)*C57	**7**
70	Scrap asphalt	Road aggregate	51.9	=C57-C68-C69	
71	Scrap concrete	Bituminous aggregate	11	=135*0.9072*0.09	**8**
72	Scrap concrete	Concrete aggregate	7.35	=135*0.9072*0.06	**8**
73	Scrap concrete	Fill	8.57	=135*0.9072*0.07	**8**
74	Scrap concrete	Landfill	64.5	=D105-C71-C72-C73-C75-C76-C77	
75	Scrap concrete	Other, construction	8.57	=135*0.9072*0.07	**8**
76	Scrap concrete	Shore armour	3.67	=135*0.9072*0.03	**8**
77	Scrap concrete	Road aggregate	83.3	=135*0.9072*0.68	**8**
78	Slag	Clinker	0.792	='R'!B53	
79	Slag	SCM	1.71	='R'!C34	
80	Water	Cement plaster	3.18	='C'!G52	
81	Water	Concrete	103	='C'!G51	
82	***1** 350M US tons C&D waste of which <60% (55%) assumed concrete (CMRA, 2006 in WBCSD, 2009; see also Cochran & Townsend, Fig. 5), assuming waste share equals construction share				
83	***2** Recycling of cement kiln dust is likely to be significantly underestimated (van Oss, 2005a, p. 16.4)				
84	***3** CO_2 from calcination (excl. combustion) of 553 kg/tonne (Marceau, Nisbet & VanGeem, 2010, p. i)				
85	***4** Arithmetic mean of the (sub)base end-of-life fractions from Bloomquist et al. (1993, Table 17), assuming 3 surface replacements per subbase replacement				
86	***5** FHWA & USEPA (1993, Table 4) extended to 2002 by Cochran & Townsend (in press)				
87	***6** 33% of scrap asphalt road is estimated to be recycled into hot-mix asphalt (Sullivan, 1996, p. 1)				
88	***7** Using a recycling rate of 73 out of 91 tonnes from 1992/3 (FHWA & USEPA, 1993, Table 4)				
89	***8** 135M US tons CMRA (2006) mid. est., in USEPA (2009); fractions from Deal (1997), in Low (2005)				
90					
91	**MASS BALANCE**	**Outflow**	**Inflow**		
92	Asphalt	421	421		
93	Asphalt shingles	13.1	13.1		
94	Bituminous aggregate	401	401		
95	Bituminous material	21.8	21.8		
96	Clinker	139	139		
97	Cement	125	125		
98	Cement kiln dust	11.8	11.8		
99	Cement plaster	21.9	21.9		
100	Concrete	1090	1090		
101	Concrete aggregate	869	869		
102	Road aggregate	851	851		
103	SCM	12.8	12.8		
104	Scrap asphalt	110	110		
105	Scrap concrete	187	187		

Appendix A, Raw Materials (Worksheet "R")

	A	B	C	D
1	**VIRGIN AGGREGATES**	**Crushed Stone**	**Sand&Gravel**	**Tot. Agg.**
2	Concrete aggregate	325.28	508.82	834.10
3	Bituminous aggregate	207.27	146.88	354.14
4	Road base and coverings	457.39	258.01	715.40
5	Plaster and gunite sands	0.00	21.42	21.42
6	Concrete products (blocks, bricks, pipe, etc.)	0.00	19.57	19.57
7	Asphalt shingle (roofing) granules	4.45	0.00	4.45
8	Fill	139.07	172.83	311.91
9	Riprap and jetty stone	51.89	0.00	51.89
10	Railroad ballast	23.52	0.00	23.52
11	Filter stone	22.96	0.00	22.96
12	Other construction	18.39	20.43	38.82
13	Cement manufacture	124.18	2.86	127.04
14	Lime manufacture	36.07	0.00	36.07
15	Agricultural uses	24.85	0.00	24.85
16	Other, non-construction	94.68	24.64	119.32
17	*Total*	*1530.00*	*1175.46*	*2705.46*
18	*Crushed stone:* Tepordei (2005) Table 13. "Unspecified" and "other" uses redistributed evenly across all categories except: concrete aggregate [calculated from total required on "C" worksheet minus concrete aggregates from sand & gravel plants], cement [from van Oss (2005a) Table 6], lime [19.2 Mt from Miller (2005), assumed production from 95% $CaCO_3$ limestone] and roofing granules [assumed accurate as few customers]. In these cases, the amounts remaining after fixed amounts deducted were redistributed evenly within and across categories.			
19	*Sand & gravel:* Bolen (2005) Table 6. "Unspecified" uses redistributed evenly across all categories. Industrial applications for sand (silica) from Dolley (2005).			
20				
21	**ASPHALT SHINGLES**	**Mass % ***	**Manufacture**	**Re-roofing**
22	Asphalt (incl. asphalt-based adhesives)	20.0%	2.62	
23	Filler (limestone, silica)	36.0%	4.71	
24	Granules (painted, finely crushed granite)	34.0%	4.45	
25	Mat (fiberglass)	6.0%	0.79	
26	Back dust (limestone or silica sand)	4.0%	0.52	
27	*Total ***	*100.0%*	*13.09*	
28	Waste (manufacturing scrap + tear-offs) ***		1.45	8.53
29	*Product to market*		*11.64*	
30	* % breakdown est. from Jameson (2008); ** Total = 4450/34%; *** NAHB cited in Jameson (2008)			
31				
32	**SUPPLEMENTARY CEMENTITIOUS MATERIALS**	**Ashes**	**Slags**	**Total**
33	Cement *	3.39	1.13	4.51
34	Concrete **	11.13	1.71	12.84
35	*Total*	*14.52*	*2.84*	*17.35*
36	* van Oss (2005a) Table 6; ** AACA (2004) for ashes, van Oss (2005b) Tables 1 and 3 for slags			
37				
38	**CEMENT PRODUCTION AND CONSUMPTION ***	**Clinker**	**Cement**	
39	Production	81.88	92.84	
40	Imports	1.81	21.02	
41	Exports	0.00	0.84	
42	Taken from stock	0.00	1.07	
43	*Apparent consumption*	*83.69*	*114.09*	
44	* based on van Oss (2005a) Table 1			
45				
46				

Appendix A, Raw Materials (Worksheet "R")

	A	B	C	D
47	**CEMENT INPUTS ***	**Clinker**	**Cement**	**Combined**
48	Crushed rock (limestone, cement rock, sandstone)	122.54	1.64	124.18
49	Clay, shale, other aluminous	7.20	0.01	7.21
50	Sand and calcium silicate	2.86	0.00	2.86
51	Cement kiln dust	0.29	0.15	0.44
52	Fuel ash	3.35	0.04	3.39
53	Slags	0.79	0.33	1.13
54	Gypsum and anhydrite	0.00	5.00	5.00
55	Other	1.97	0.09	2.06
56	*Total domestic*	*139.00*	*7.26*	*146.26*
57	Imports	0.00	4.24	4.24
58	*Total*	*139.00*	*11.50*	*150.50*
59	* based on van Oss (2005a) Table 6			
60				
61	**CLINKER=>CEMENT MASS BALANCE ***	**Mass**		
62	Clinker production (exluding Puerto Rico)	81.88		
63	Clinker imports (exluding Puerto Rico)	1.81		
64	Additions during milling (Puerto Rico ass. negligible)	7.26		
65	*Cement produced in the USA*	*90.95*		
66	Cement imports (exluding Puerto Rico)	21.02		
67	Cement exports (exluding Puerto Rico)	0.84		
68	Cement from stock (exluding Puerto Rico)	1.07		
69	*Apparent consumption of Portland cement (+blends)*	*112.20*		
70	-- Portland cement (including blends)	107.46		
71	-- Masonry cement	4.73		
72	*Apparent consumption of Portland + SCMs*	*125.04*		
73	-- Portland cement (including blends)	119.76		
74	-- Masonry cement	5.28		
75	* based on van Oss (2005a) Table 1			
76				
77	**CEMENT+SCM BY END USE**	**Mass**	**Mass %**	**Distributed**
78	Ready-mixed concrete *	79.00	74.17%	88.83
79	*Concrete products **	*14.70*	*13.80%*	*16.53*
80	--brick/block	6.23	52.22%	8.63
81	--precast	3.81	31.94%	5.28
82	--pipe	1.89	15.84%	2.62
83	--others	2.77	0.00%	0.00
84	*Contractors **	*6.79*	*6.38%*	*7.63*
85	--airport	0.22	4.80%	0.37
86	--road paving	3.60	80.45%	6.14
87	--soil cement	0.66	14.75%	1.13
88	--other	2.32	0.00%	0.00
89	Building material dealers *	3.61	3.39%	4.06
90	Oil well, mining, and waste stabilization *	1.44	1.35%	1.62
91	Government and miscellaneous *	0.97	0.91%	1.09
92	*Total portland cement used in the USA ***	*107.70*	*100.00%*	*119.76*
93	Masonry cement used in the USA **	4.75		5.28
94	*Apparent consumption within the USA ***	*112.44*		*125.04*
95	* van Oss (2005a) Table 15; ** from van Oss (2005a) Table 9 minus SCM in cement from Table 6			

Appendix A, Cement and Concrete (Worksheet "C")

	A	B	C	D	E	F	G	H	I
1	**CEMENT USE BY TYPE** [Low (2005) Table D 6 with data from "CEMENT+SCM BY END USE"]								
2		**Mass**	**Mass %**						
3	Ready mix	88.86	71.0%						
4	Concrete products	16.53	13.2%						
5	Building materials	4.06	3.2%						
6	Mortar	5.28	4.2%						
7	Roads	6.14	4.9%						
8	Other infrastructure	4.20	3.4%						
9	Total	125.08	100.0%						
10									
11	**ESTIMATED CEMENT USE BY TYPE AND END USE ***								
12		Buildings	Roads	Other	*Total*				
13	Ready-mix	33.3%	32.0%	7.0%	*72.3%*				
14	Concrete products	6.2%		7.0%	*13.2%*				
15	Building materials	3.2%			*3.2%*				
16	Mortar	4.2%			*4.2%*				
17	Other infrastructure directly			7.0%	*7.0%*				
18	*Total ***	*47.0%*	*32.0%*	*21.0%*	*100.0%*				
19	* Low (2005) Table 6.6 with updated data; ** Portland Cement Association, cited in Low (2005) p.188								
20									
21	**RAW MATERIALS BY CONCRETE MIX ***								
22		**Raw materials (kg/m^3)**							
23	**Concrete Product**	**Cementitious Materials**	**Water**	**Fine Agg.**	**Coarse Agg.**	**Silica Fume**	**Unit Mass**	**Solid Waste**	
24	20 MPa Ready-Mix	223	141	830	1100	0	2294	24	
25	30 MPa Ready-Mix	279	141	770	1200	0	2390	24	
26	35 MPa Ready-Mix	335	141	710	1200	0	2386	24	
27	Brick/Block	209	142	2033	0	0	2384	32	
28	50 MPa Precast	504	178	550	1100	0	2332	76	
29	70 MPa Precast	445	136	610	1100	56	2347	76	
30	Arch. Precast	386	154	740	1100	0	2380	76	
31	Pipes	280	109			0	2403	76	
32	Mortar	307	185	785	0	0	1277	0	
33	Road mix	279	395	650	999	0	2323	24	
34	* Low (2005) Tables D 7, D 9-13; solid waste figures from Marceau, Nisbet & VanGeem (2007)								
35									
36	**EST. BREAKDOWN OF CEMENT USE BY CONCRETE MIX** [based on Low (2005) Table 6.10]								
37	**Cooncrete Type**	**Product**	**Mass %**	**CM**	**Concrete**	**Agg.**	**Water**	**Scrap**	**To infra.**
38	Ready-mix	20 MPa	36.3%	45.367	466.6932	392.6	28.69	4.8826	461.8106
39		30 MPa	1.2%	1.5122	12.95434	10.68	0.764	0.1301	12.82426
40		35 MPa	2.8%	3.5286	25.13183	20.12	1.485	0.2528	24.87903
41		Road mix	32.0%	40.012	333.1454	236.5	56.65	3.4419	329.7035
42		*Subtotal*	*72.3%*	*90.42*	*837.925*	*659.9*	*87.58*	*8.707*	*829.217*
43	Concrete products	Brick/block	6.9%	8.6316	98.4584	83.96	5.865	1.3164	97.14198
44		50 MPa	1.4%	1.7596	8.141539	5.761	0.621	0.2653	7.876206
45		70 MPa	1.4%	1.7596	9.28029	6.762	0.538	0.3005	8.979778
46		Precast	1.4%	1.7596	10.84921	8.388	0.702	0.3464	10.50277
47		Pipes	2.1%	2.6186	22.47307	18.84	1.019	0.7108	21.76231
48		*Subtotal*	*13.2%*	*16.529*	*149.203*	*123.7*	*8.745*	*2.939*	*146.263*
49	Building materials		3.2%	4.0591	41.75646	35.13	2.567	0	41.75646
50	Other infrastructure		7.0%	8.7526	62.33938	49.9	3.684	0.626	61.71338
51	*Total Portland Cement*		*95.8%*	*119.76*	*1091.22*	*868.7*	*102.6*	*12.27*	*1078.95*
52	Mortar		4.2%	5.2764	21.94781	13.49	3.18	0	21.94781
53	*Total*		*100.0%*	*125.04*	*1113.17*	*882.2*	*105.8*	*12.27*	*1100.9*