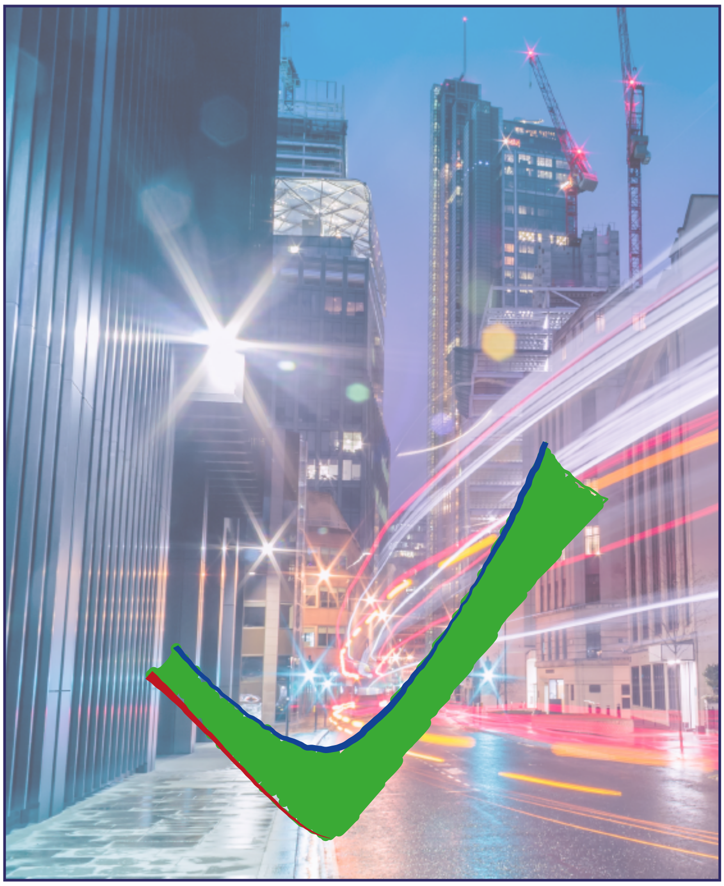
Unlocking Absolute Zero



Overcoming implementation barriers on the path to delivering zero emissions by 2050

UK FIRES

Absolute Zero Energy Innovation Opportunities

UK demand for energy-intensive materials is growing, driving increased emissions in the UK and abroad. UK FIRES is a research programme sponsored by the UK Government, aiming to support a renaissance of UK Industry, compatible with our legal commitment to zero emissions by 2050 by placing Resource Efficiency at the heart of the UK's Future Industrial Strategy.

Industry is the most challenging sector for climate mitigation - it's already energy efficient and there are no substitutes available at scale for the energy-intensive bulk materials - steel, cement, plastic, paper and aluminium. UK FIRES is therefore working towards an industrial renaissance in the UK, with high-value climate-safe UK businesses delivering goods and services compatible with the UK's legal commitment to zero emissions and with much less new material production.

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Executive Summary

Our commitment to eliminate greenhouse gas emissions by 2050 calls for deep, systemic change in the way that we use energy and energy-intensive materials such as steel, aluminium and cement. Many technically viable options for change remain underexploited despite the ambitious climate change target set into UK law. This report explores why we continue to use excess energy and materials in the way that we construct buildings, manufacture cars and extract ores.

The nature of the challenge

By law, the UK is committed to eliminating all emissions by 2050. We are currently not on track to reach this target, which calls for radical change in the way that we meet the needs of our society. Even if the rapid expansion of renewable energy achieved in the UK over the last decade were to continue, and all currently available technology were applied to electrify processes and improve efficiency, we would still need to reduce demand for energy by 60% (Absolute Zero: **www.ukfires.org/absolute-zero**).

Options for change in key sectors

Despite the severity of the climate change target put into UK law, we continue to be wasteful in our use of key energy-intensive materials. For example, we persist in designing cars that weigh significantly more than they need to and waste about a quarter of sheet metal unnecessarily in their production, and we persist in designing buildings that require 30% more steel than needed.

What is hampering change?

One way to think about change is as a balance between motivation and difficulty: change happens when motivation exceeds the difficulty of making the change. Change may not happen simply because incentives are inadequate. But even when change is desirable, it may still not be possible to enact quickly due to the configuration of existing supply chains and processes; we refer to this barrier to change as 'lock-in'. Lock-in captures the idea that the potential for change in the future is to some extent predicated on what has happened in the past.

The nature of lock-in varies across industries; we consider examples in construction, automotive and mining. In the construction sector, designers tend to adapt previous building designs and use heuristics rather than explore the full range of options available when designing new buildings. Similarly, in the automotive sector, the car body architecture of a new model is often carried over from previous ones with the consequence that, despite the continual release of new models, cars remain locked-in to a particular design paradigm. Furthermore, in cases when more holistic car design changes are implemented, the implications for material demand, and hence emissions, are only calculated late in the design process after many key decisions have already been made. In contrast with automotive, the mining sector lacks the steady drum beat of new product launch and is notoriously cyclic. It is also more capital-intensive, co-dependencies between equipment suppliers and mining companies and long payback periods lead to a reticence to adopt novel, more efficient equipment.

From the detailed picture in specific industries, common lessons emerge: Three types of lock-in appear to hamper change:

Historical lock-in: when previous technology and design choices limit options to adapt to future needs.

Informational lock-in: when choices are under-informed either because of a lack of information or because of a surplus of information which is costly to analyse.

Coordination lock-in: when some players are less able to change because they suffer from other forms of lock-in or because they actively foster barriers to change to protect their competitive position.

Moving forward

Our climate change commitments call for deep, systemic change. The nature of lock-in within different industries reveals opportunities for change rooted in the intricacies of current decision-making processes and organisational structures. The first steps for managers seeking to overcome lock-in are to:

1. introduce different metrics into early stage decision processes, to raise awareness of opportunities;
2. introduce new people or resources into existing teams, to create a new focus on the carbon-saving opportunities;
3. expand the network of players involved in the activities surrounding the opportunities, in order to challenge embedded orthodoxies and to create a more dynamic exploration of alternatives.

How does lock-in prevent change?

Key Message: 'Lock-in' captures the idea that the potential for change in the future is to some extent predicated on what has happened in the past. This could be due to the nature of relationships (coordination lock-in), due to historical practices and technology choices (historical lock-in), or due to the availability of information (informational lock-in).

Coordination lock-in

Coordination lock-in happens when multiple stakeholders must work together to accomplish an objective. Lock-in occurs when one stakeholder is able to change, but other stakeholders in the system prevent them from doing so. This may be because other stakeholders are involuntarily constrained or because they deliberately resist change so as to protect their competitive position. The difficulty increases rapidly with the number of stakeholders involved.

Coordination lock-in is relevant to reconfiguring supply chains to improve resource efficiency. Examples include steel re-use in construction, where new relationships need to be established between actors in the value chain. It also applies in the capital-intensive mining industry, where co-dependencies between equipment suppliers and mining companies can lead to a reluctance to adopt novel, more efficient equipment.

Historical lock-in

Historical lock-in happens when previous decisions limit future options, either directly, for example through financial investment in long-lived assets, or indirectly, for example through political capital being invested in decisions that are difficult to reverse.

The importance of historical lock-in depends on the timescale of the industry in question. Different industries have different timescales for the depreciation of capital assets and for design decisions. Airframes last for multiple decades, car platforms are redesigned every decade, and car models are refreshed every two years. Buildings are designed and constructed within the time horizon of the individual project.

Historical lock-in confounds the rapid decarbonisation of manufacturing and construction processes. As explained by the Material Economics report, Industrial Transformation 2050, key decisions made now risk locking in future choices. The report highlights that "EU companies will make important investment decisions in the next few years.[1] Each will create a risk of lock-in (to high emission pathways) unless low-CO2 options are viable at these forks in the road".

Informational lock-in

Informational lock-in happens when potential improvements are not implemented due to a lack of information or because of a surplus of information that is costly to analyse. Decision-makers may not be aware change is possible, they may not have enough evidence to make a change, or even if they do, they may not have the process in place to use the information. The bigger the gap between current operations and what is possible, the bigger the risk of this lock-in occurring.

Examples include the structural design of buildings where, due to time pressures and complexity, the optimum design is often not achieved (see the case study on building design). More generally, the Resources and Waste Strategy for England identified insufficient information as one of the key barriers to increasing the resource efficiency of businesses.[2] This was especially the case for smaller businesses that often lack the resources needed for research.

Analysing lock-in

Key Message: The idea of lock-in emphasises that change is rooted in the intricacies of current decision-making processes, from which it follows that the nature of the lock-in needs to be analysed on a granular, case-specific basis. Nevertheless, common themes do emerge, and models can be used to help gauge the difficulty of transitions more generally.

Case studies

The nature of lock-in will vary depending on many factors such as the nature of relationships within supply chains, the capital intensity of production, the intensity of competition, design practices and the structure of decision-making processes. In this report we explore six specific cases of lock-in, namely: reusing steel beams in buildings; building design optimisation; reducing wastage in car manufacturing; lightweighting vehicles; dry bulk sorting of ores; and, the shift away from diesel transport in mines.

Modelling the strength of lock-in

We use a stylised model to gauge the difficulty associated with different transitions. Our method is derived from graph theory: The current state and the desired future state, are represented by a set of block diagrams, be they of a production line in a factory or a supply chain involving many actors. The model allows these stylised diagrams to be modified in three ways (Figure 1):

1. adjust the capability of existing actors (option 1 on the left or option 2 on the right);
2. add or remove actors (option 2 on the left or option 1 on the right);
3. reorganise the configuration.

The model starts from a depiction of the current state and randomly modifies it (according to the rules above) until the desired state is reached. We interpret the number of random modifications required before the desired state is reached as an indicator of the difficulty of the transition. As a general rule, change is harder when there is a greater gap between the current state and the desired state, and when the target outcome is more specific.

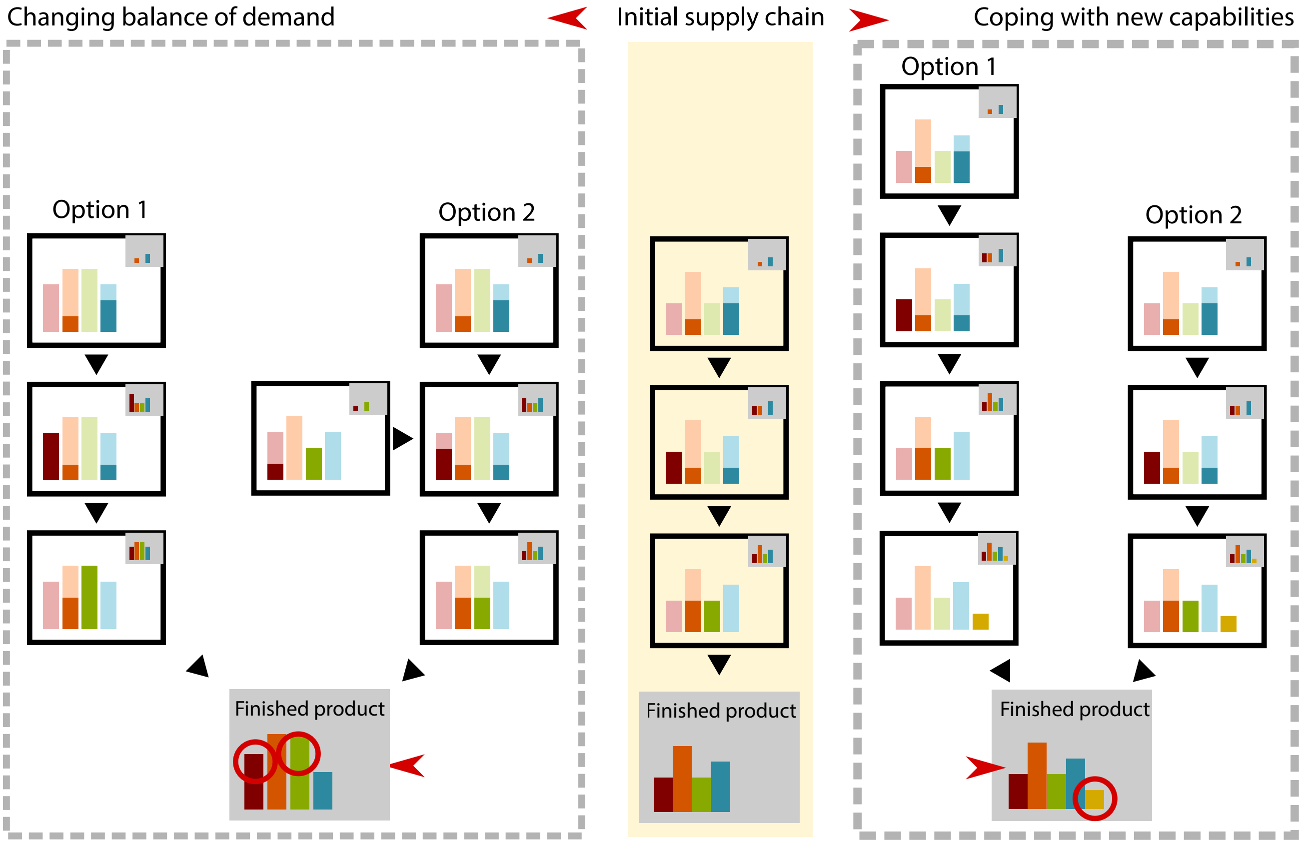

Figure 1: How supply changes can be reconfigured. The coloured bars represent operations or processes, and each box is a supplier or a team.

Lock-in analysis for construction

Key Message: In the construction sector, designers operate under high time pressure to design one-of-a-kind buildings. They tend to adapt designs for similar buildings rather than explore the full scope of design options available to them. This locks in inefficient design. At the end of the building's life, steel sections that could be re-used are routinely recycled at an unnecessary energy premium. Optimisation software and specialist contractors can help to overcome obstacles to change in the sector.

Case Study 1: Steel Reuse

Reusing, instead of scrapping, steel sections from deconstructed buildings reduces emissions. There are many barriers to steel re-use, for example the certification of the steel or the perception that used elements are inferior to new ones. Many strategies have been proposed to improve steel re-use, for example through streamlined certification processes and Building Information Models used to establish precise and up-to-date material availability databases. Currently, however, only 5% of construction steel in the UK is re-used, despite most of it being in the form of standard beams and columns which could be re-used after minor reconditioning[3].

Modelling the process change

In Figure 1, we compare two scenarios that depart from the usual sequence: Steel component manufacture - Building fabrication - Building demolition.

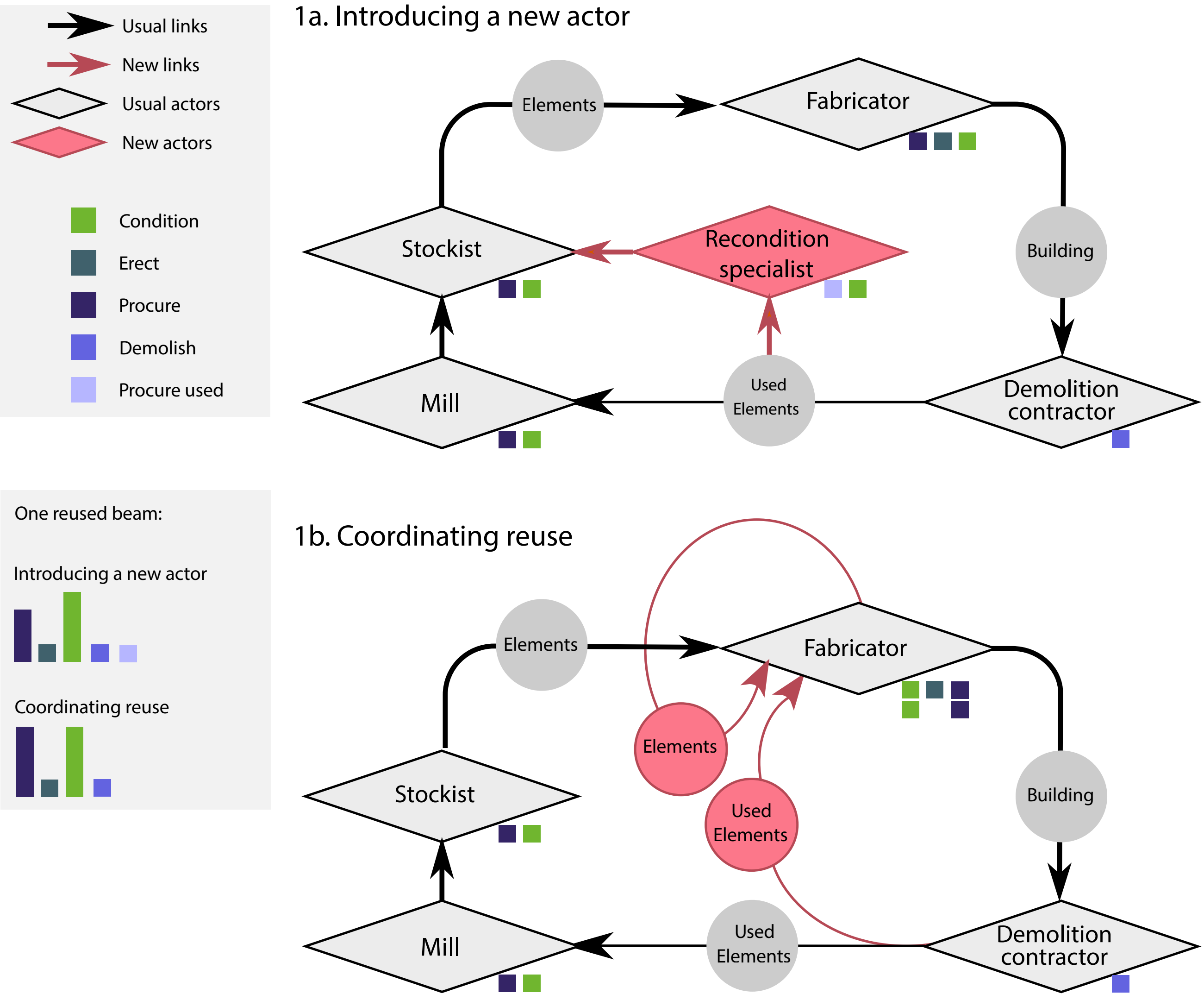

Figure 1: Modelling options for re-use of steel beams in building construction

a. Introducing a new actor: A reconditioning specialist is introduced to the processes to supply the existing stockist. They collect used sections and recondition the beams so that they can be sold on 'as new'.

b. Coordinating re-use: The fabricators must get sections from the demolition contractors and, when the necessary sections are unavailable, procure as they would normally from the stockist. The sections procured from the demolition contractors must be reconditioned before being fabricated to the required specifications.

Reconditioning requires the same skills and equipment as needed for fabrication of beams. Certification of the fabrication follows the same process. Certifying the steel itself is not currently possible because CE marking on steel beams can only be done by foundries. The physical properties guaranteed by the certificate can be verified through testing, and an equivalent - but not standard - certificate can be provided.[3]

Figure 1 illustrates how the supply chain is modelled using block diagrams for this analysis. The 'introducing a new actor' flow chart shows the process change required if a reconditioning specialist is introduced, whereas the 'coordinating re-use' diagram shows the flow for steel re-use directly from the demolition contractor. Coloured blocks mark the operations each actor performs. Arrows indicate the connections between the actors as the beams are produced, fabricated, erected, and removed after demolition. The circles on the arrow indicate the material or semi-finished product being passed along.

A specialised 'procure used beams' operation has been added to the 'new actor' scenario. In this case the bulk procurement of used beams is a specialist task which requires knowledge of demolition activities across the region of supply. Instead, in the 'Coordinating re-use' scenario used beams are procured from a known source as a one-off. Usually this will not fully cover the needs of the new build, and the shortfall will be supplied by the stockist.

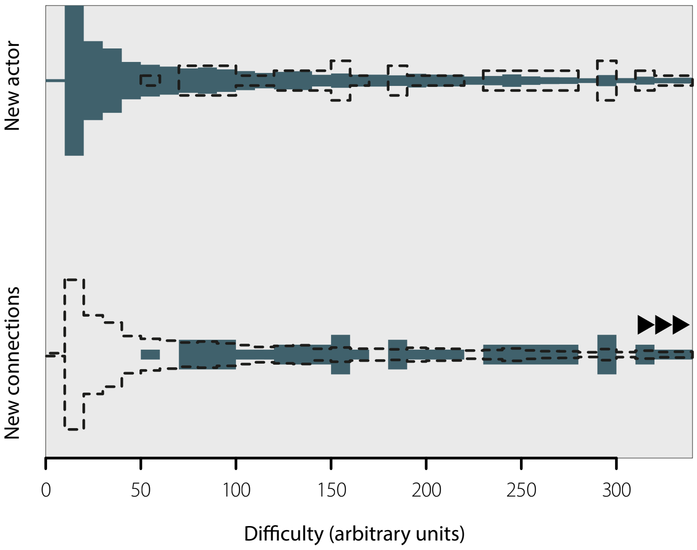

Figure 2

This example is a practical case of 'thinking outside the box' where instead of relying only on known partners, the solution lies in finding new ones, responsible for doing what appeared to be a core business operation. Managers looking for material efficiency options should approach the problem hollistically: opportunities often lie in new business networks and operations, as well as improved products.

The model suggests that the new actor scenario is better in almost all cases (Figure 2).

The lock: Re-certification is tightly regulated; supply of used beams is intermittent with low visibility

A solution: Introduce a new actor, a company that specialises in sale, aggregation and re-certification of used beams

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Case study 2: Building design optimisation

Almost every building, particularly a larger commercial building, is 'one of a kind', every site is slightly different, with likely different requirements in terms of foundations, wind loads and exposure. To guarantee the safety of structures, the design of buildings follows rules or 'building codes' which are extremely detailed. Furthermore, the design of buildings occurs under considerable time pressure. Simple buildings with all structural parameters fixed can be built according to the code in tens, or even hundreds, of ways. With so many design options available, informational lock-in can occur making it too difficult for a designer to optimise for lower embodied emissions: rather than optimising each new building, previous designs are adapted.

A technological solution for this type of informational lock-in is a computer modelling tool which translates the building codes and specific site parameters into large numbers of preliminary designs. An example of the results of such a tool is shown in Figure 3, these possible solutions can help the designer to make better informed decisions at the outset of the design process by revealing material efficiency trade-offs. By allowing designers to quickly analyse all options available relative to the particular constraints of the project, the tool helps designers to find tailored, optimised solutions and avoids overspecification caused by adapting designs from similar buildings.

Modelling the process change

Figure 3 illustrates the effect of such a tool on the map of possible changes. The tool only affects the capabilities of the existing actors - there is no block diagram equivalent to Figure 1. It reduces lock-in mostly by opening up many options. Companies wanting to prevent informational lock-in need to take action to make sure they keep their technological edge, including for example, R&D programmes to develop new tools, and design exercises to increase the portfolio of options for meeting real demands.

Building new design tools is a difficult task, frequently outside the in-house expertise. Nonetheless, this strategy, widely applicable across sectors, can hold great promise. Crucially, the process of building the tool requires a detailed specification of the design process, a valuable exercise which has the potential on its own to help overcome lock-in. In the face of large disruption caused

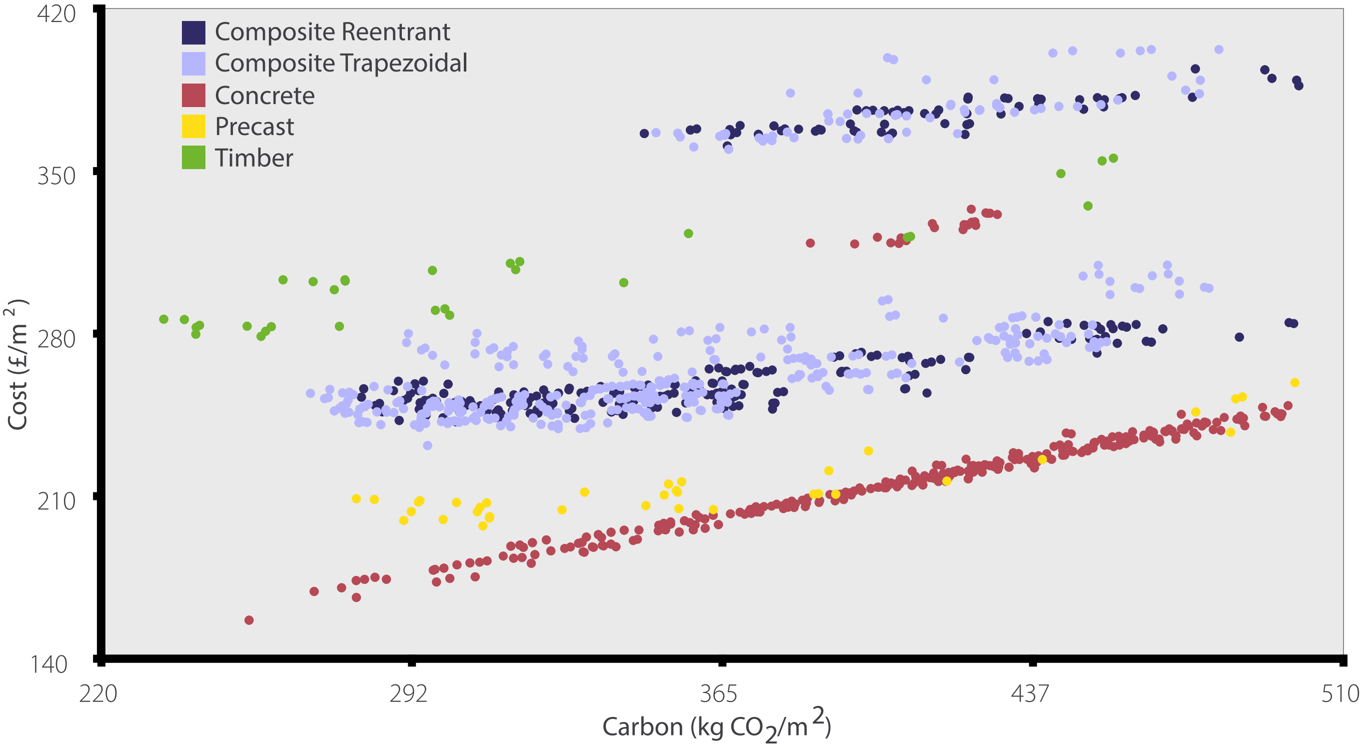

Figure 3: Example results from building design optimisation software every dot is a different layout and decking combination. The graph shows the carbon cost trade-offs for different designs for the same building.

by abrupt changes in legislation or consumer demands, being flexible is key. Being flexible means having more options – fortunately, looking for these options is a good way to grow businesses in any situation! Looking forward, managers should think about the potential of R&D not only as a source of future revenue streams, but as a safeguard against disruption.

The lock: The design process is highly codified. Companies and individuals are penalised if they depart from the codes. There is neither budget, nor time, to undertake whole system design. Instead, it is common practice to reuse large elements of earlier designs

A solution: Use of computer models to allow design options to be identified and evaluated quickly - from system-level to component-level

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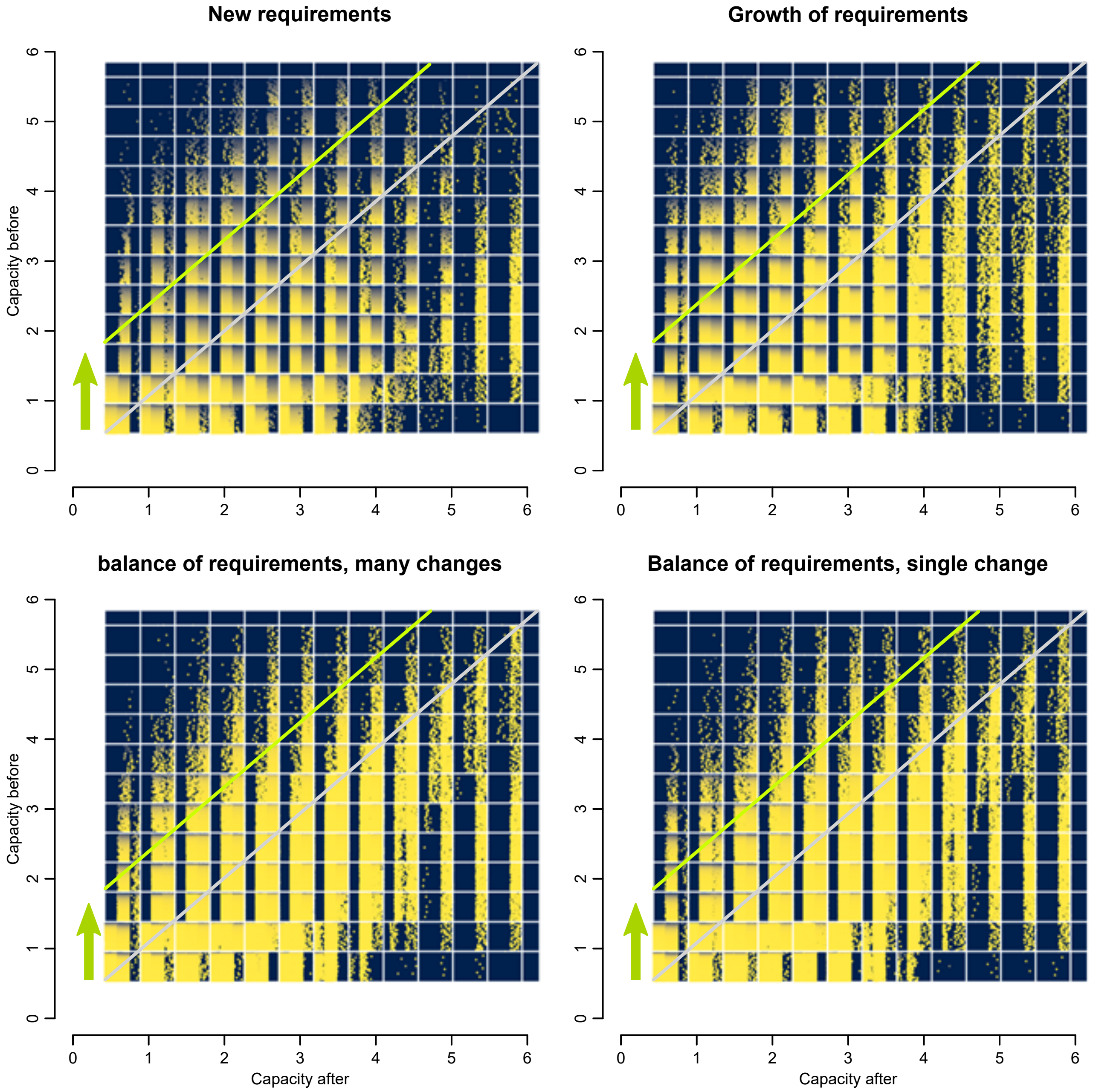

Figure 4: Mapping the probability of success (indicated by lighter areas) for optimising embodied emissions in building design. The arrow demonstrates the effect of introducing new optimisation software to the scenarios modelled. In each case, change is more likely to be successful with the new software introduced: the area of yellow lying under the line is larger, marking more, successful transitions.

Lock-in Analysis for the transport sector

Key Message: The transportation sector, especially the car industry, is undergoing a number of significant shifts. The industry is moving towards electric drivetrains and lighter aluminium bodies whilst facing decreasing consumer demand and ever more stringent environmental regulations. Despite a highly complex design process, much of the car body architecture in new models is carried over from previous models. Consequently, despite the continual release of new models, cars remain locked-in to a particular design paradigm. Even when more holistic car design changes are implemented, the material demand implications of novel designs are only calculated late in the design process after many key decisions have already been made.

Case Study 1: Material utilisation

Sheet metal utilisation in car body structures is estimated at a disappointing 56% globally.[4] The range in utilisation from its best, at 70%, to worst, at just 39%, is striking. Improving material utilisation in car-making is constrained by the nature of the car design process.

Tier One car manufacturers create multi-model 'platform designs' that form the basis for different models of vehicles produced by automotive OEMs (Figure 5). Thus, much of the body architecture, systems and components are carried over from previous models, or held in common with the OEM's other brands. As a result, cars are highly optimised, and yet also locked-in to particular design paradigms.

The Use Less Group carried out a 2018 study with Jaguar Land Rover, on implementing improved material efficiency in practice.[5] A cross-functional team was set up with the

Image: Car body structure

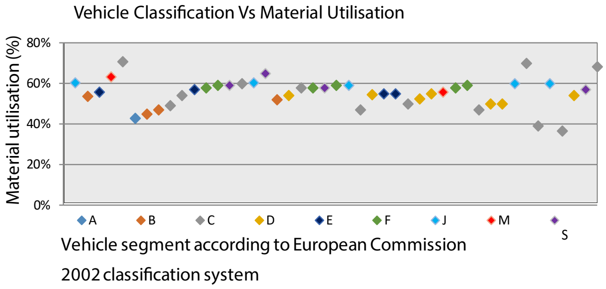

Figure 5: Car body structure b. Industry-reported material utilisation by vehicle classification type

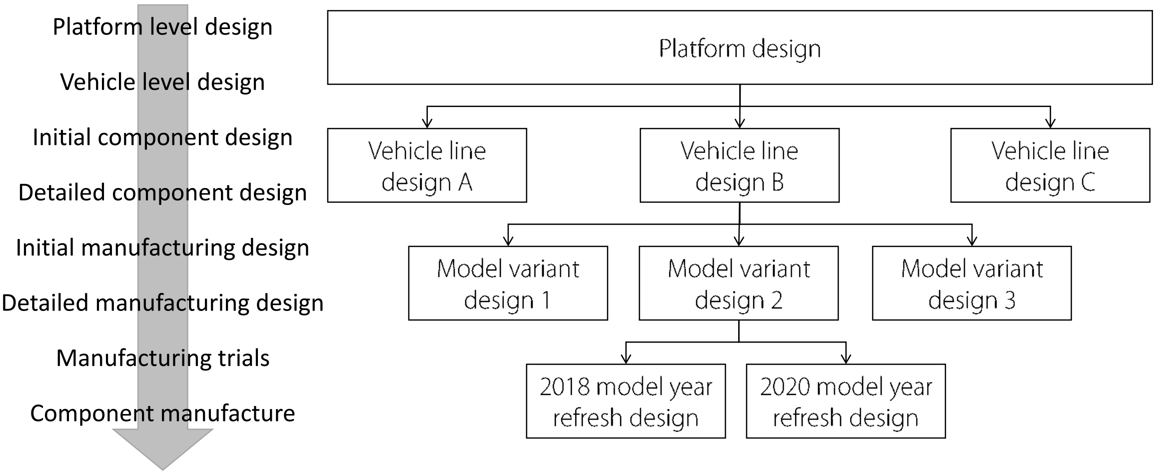

Figure 6: Typical structure of product design activities in the automotive industry

scope to make changes to five components as part of a model year refresh. A vehicle with an initial material utilisation of about 50% was chosen for the analysis.

For each component, the team analysed the stages of early component design, detailed component design and then early and detailed manufacturing process design. This process identified opportunities to improve material efficiency by 24%, estimated to save £9 million and 5 ktonnes of CO2 annually, most of which came from early component design. This is about the same as the gap between the vehicle's current utilisation, and known best practice.

However, the timing of the study coincided with detailed manufacturing process design, and it was only possible to implement 3% of the improvements available. This highlights the lock-in that automotive manufacturers face: At the point when material utilisation is known with the most certainty (detailed manufacturing design), most design decisions have already been cast, and it is very difficult to make significant improvements.

There is a clear message: Consider material utilisation much earlier in the product development cycle when considerable savings are possible. Early consideration requires better cross-functional collaboration and/or tools to show how design changes impact manufacturing processing waste. This is especially important when components are shared between models and vehicles across a design platform: there might be only one chance to make the best decision for resource efficiency for the next decade or more.

The lock: Wide-scale use of platform design principles; use of a sequential design process

A solution: adopt a holistic design process and use of cross-functional teams

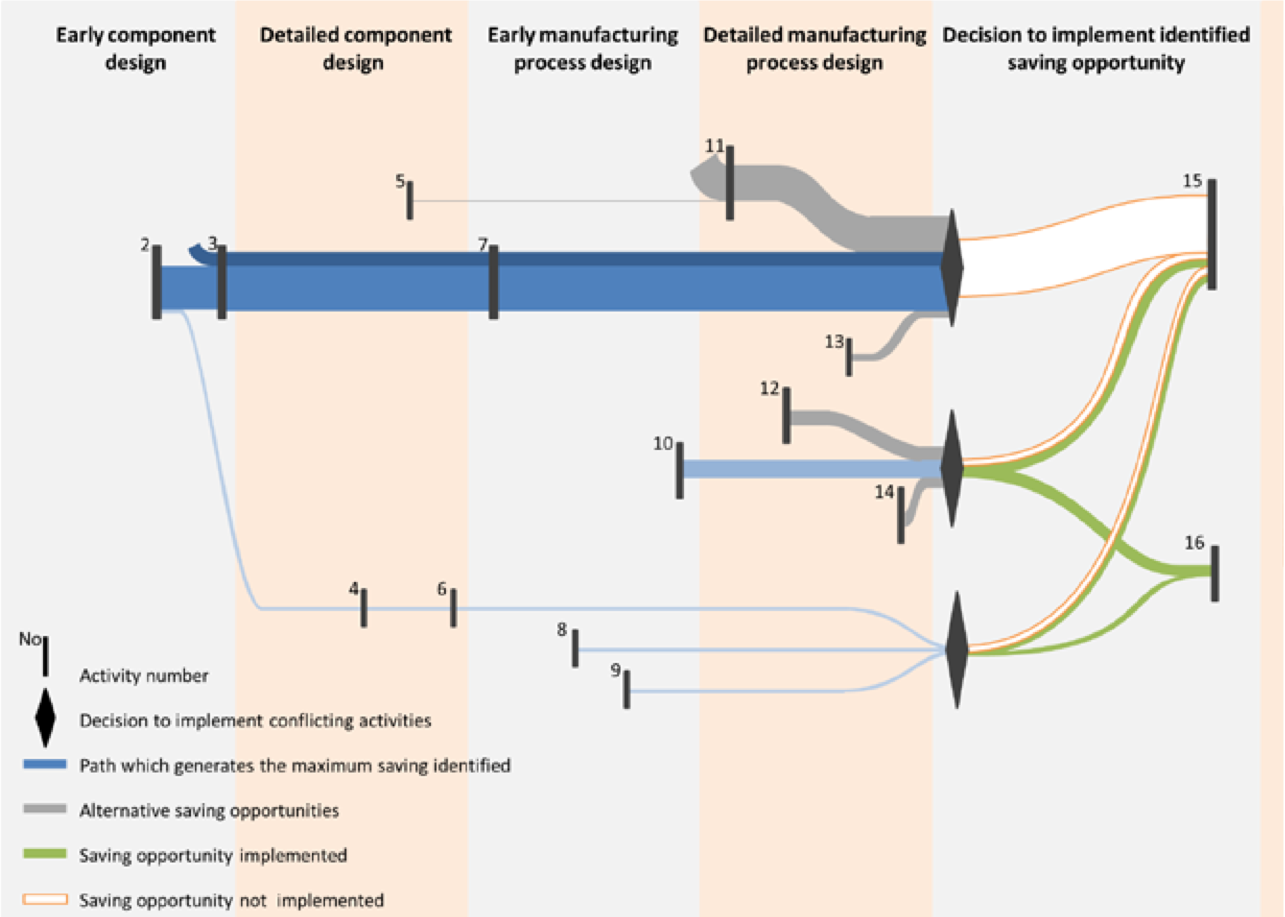

Figure 7: Material saving opportunities identified (blue and grey) and implemented (green) for five components, organised by design stage

Case study 2: Weight reduction by material substitution or downsizing

Reducing the weight of cars is a key strategy to achieve the climate change targets set into UK law. Weight reduction can be achieved by substituting some of the materials used in car manufacturing with lighter ones, and by reducing the size of cars. Of the two, size reduction has the largest effect on life cycle emissions, however, there are currently no incentives to manufacturers producing smaller cars. Consumers prefer bigger cars due to higher perceived safety, and manufacturers receive most of their profits from larger car classes. For this reason, the current motivations in the automotive sector are a barrier for change.

Here we model two configuration changes shown in Figure 8:

a. Changing material sourcing to reduce car weight by replacing mild steel with lighter wrought aluminium. This may require reconfiguration of supply chains so as to provide more wrought aluminum and less mild steel.

b. Changing both material sourcing and demand. Car clubs could act as an intermediary stakeholder between manufacturers and car users to help the manufacturers and consumers to produce and use smaller cars. Car clubs would sell car-use services to consumers instead of car ownership. This would reduce demand for cars, thus potentially making the lightweight transition easier.

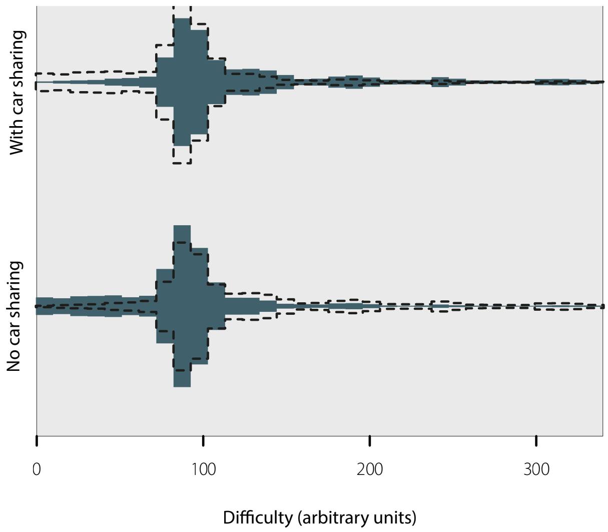

Figure 9: Probability of success of implementation of the two process changes represented in Figure 8

Figure 9 shows estimates of how difficult it would be to implement the process changes based upon our model.

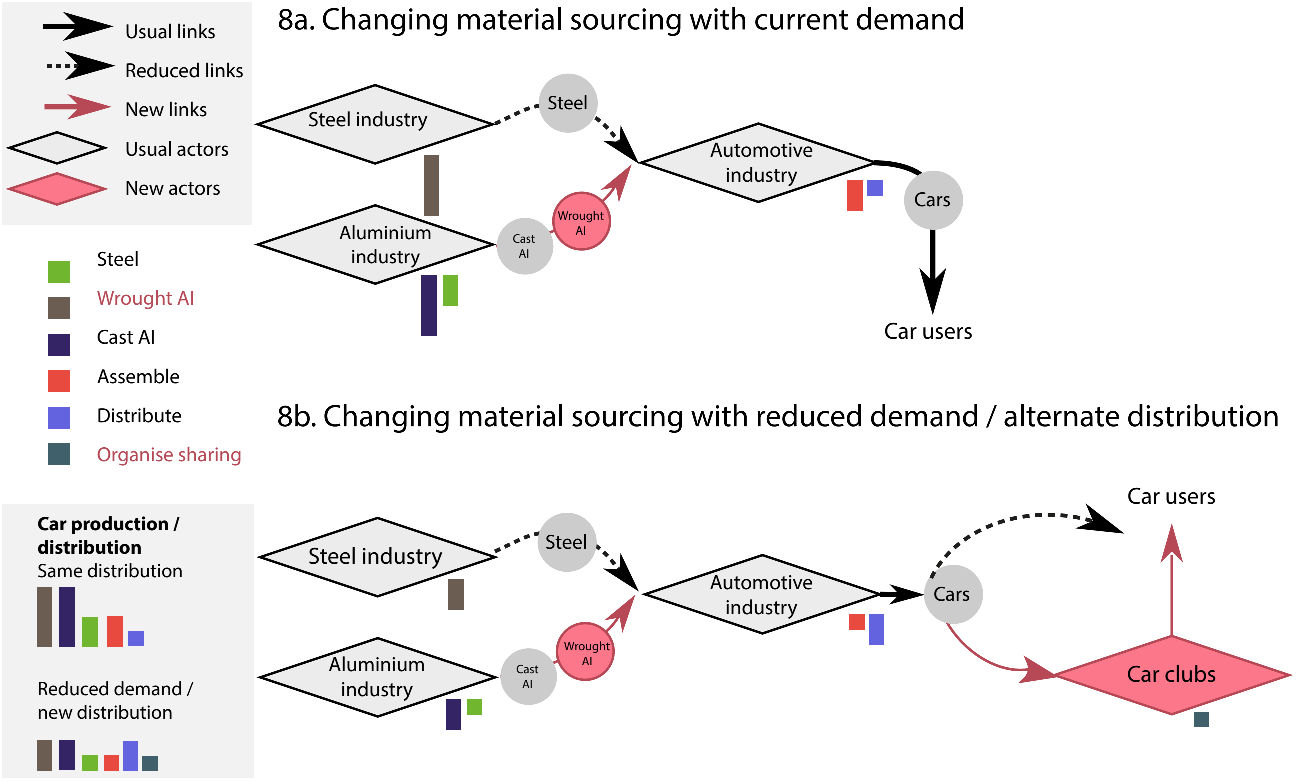

Figure 8: Block diagrams for the process change in the autonomies supply chain

The results of Figure 9 show that although both configurations have similar average difficulties of implementation, the introduction of car clubs may create additional complexities. Introducing a new stakeholder in the supply chain creates more disruption in the relationship between car manufacturers and users, and this is shown by the long tail of very hard transitions in the top graph of Figure 9. This shows how difficult it is to break the current feedback loop between car manufacturers and consumers that generates no incentives to produce and use smaller cars.

Lightweighting by material substitution leads to a moderate reduction in average car weight and operational energy uses. Manufacturers have already started implementing this transition over the past decade. However, the necessary reduction of future energy use in transport will require reducing car size. The model suggests that there are significant structural barriers to implementing this strategy.

This example looks at an industry as a whole, and modelling suggest transitions will be difficult in many cases. But this doesn't mean that all transitions or changes will be difficult. Companies best prepared for the changes ahead will thrive as their competition falls behind.

The lock: Larger vehicles are perceived by consumers as being safer than smaller vehicles, and sell for higher profits.

A solution: The status quo is hard to shift because of close alignment of the motivations of consumers and manufacturers. Car sharing is unlikely to lead to much change in vehicle sizes. A possible unlock is for governments to incentivise manufacturers to make, and consumers to buy, smaller cars, e.g. through taxes and subsidies.

Lock-in Analysis for Mining

Key Message: The mining sector is locked-in developing larger and larger operations, and thus finds it more and more difficult to change any aspect of its operations. Co-dependencies between equipment suppliers and mining companies and long payback periods lead to a reluctance to adopt novel, more efficient equipment. Vertical integration can reduce lock-in arising from inflexibility of current suppliers - new technologies which improve resource efficiency can alleviate scaling issues.

Mining and quarrying are the main source of today's materials, and expected to remain so up to and beyond 2050, although during this period, the mix of demand is likely to change. Worldwide, these activities currently account for 0.5% of primary energy supply.[6]

Mines are constrained by several factors, resulting in locked-in modes of operation. Mines are typically very large and new mines are getting bigger. For example, the mean size of copper mines has increased by 182% between 1976 to 2000, driven by a reduction in the concentration of new ore reserves.[7] It is difficult to start a mine small and get bigger in size: Once a mine layout has been decided, access routes constrain the size of equipment that can be used; this inflexibility inevitably makes it difficult to achieve optimal efficiency. Mines require large investment of financial capital, often well over $1bn, and decisions to invest typically assume operation for at least 15 years. As a result, choices are made up front to use proven and recognised technology, minimising risk but potentially locking in sub-optimal resource efficiency.

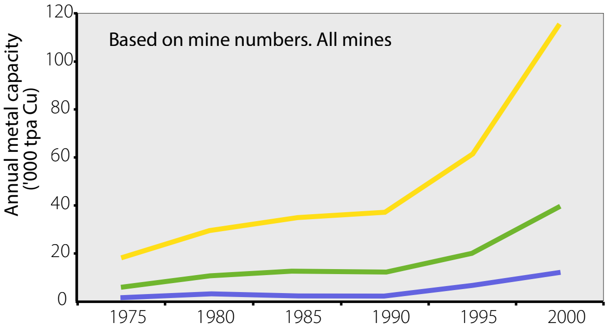

Figure 10: Copper mine sizes are getting bigger.

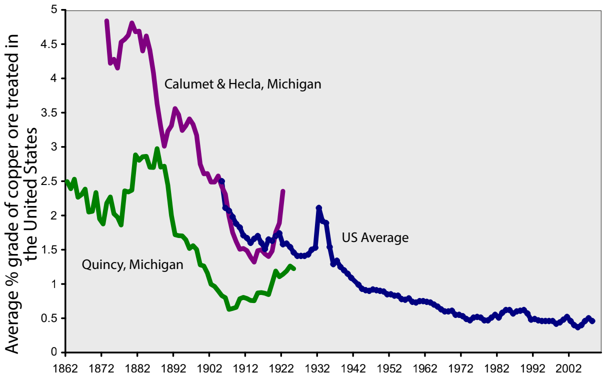

Figure 11: ...whilst ore concentrations are reducing.

Operating at such large scale, mining firms build up co-dependencies that lock in ways of working. For instance, there are few suppliers of industrial mining equipment, which limits options for change. Mines are typically the dominant source of economic activity in their local areas, so both changes to working practices or starting up new sites are highly sensitive issues.

The two biggest users of energy in mining are grinding and heavy mobile equipment. We present a case study for an innovation related to each.

Case Study 1: Dry bulk sorting

In mining, as much as 40% of the energy is used for grinding rocks into particles of sizes below 100µm, allowing the resource to be separated from the fines.[8] Usually, the mine is divided into small regions, and in each, the average concentration of resource is determined; and a decision is taken to reject it or go ahead with grinding.

Dry bulk sorting is a technology for scanning the output material from the first stage of crushing and then discarding batches with weaker concentration. This means that the resource efficiency of the subsequent grinding can be significantly improved since the input material is of higher concentration, outweighing the extra energy for crushing of possibly sub-par ore. For a typical copper mine, crushing and grinding resource efficiency can improve by about 15%.[9]

Introduction of any new equipment involves staff training in operating and maintenance procedures. However, the introduction faces no fundamental blocks. In return, dry bulk sorting enables favourable changes to the criteria for selecting regions for extraction, and to the criteria for mine abandonment. The effects could be far-reaching: enabling profitability at smaller scale by a more gradual ramp-up of operations, and making a larger range of sites profitable.

The lock: the industry (investors, suppliers and mining companies) are locked into a paradigm that profitability is only achieved through increasing economies of scale

A solution: Dry bulk sorting allows selection of ore of higher value for subsequent processing. It allows the mine to become profitable sooner, and at smaller scale, transforming the investment cycle

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Case Study 2: Trucks shift from diesel

Up to 20% of the energy associated with open-pit mining – the most ubiquitous form of resource extraction - is spent powering heavy mobile equipment, with diesel.[9] These trucks are often very large, with engine sizes exceeding 1MW. Eliminating these emissions requires breaking out of existing practices, up and down the supply chain. One solution is being trialed at Mogolakwena mine, near Mokopane, South Africa. It is projected to be cost positive in the long-run, but highlights the extent of lock-in that must be overcome.

The trucks to be converted are 290 tonne payload diesel-electric trucks supplied by a major equipment provider. They have a 2MW diesel electric generator, sized to power the fully-loaded truck as it lifts ores up the steep slopes of the mine, but also to supply power to several ancillary systems. Diesel is transported to site by commercial tankers. This system is shown in Figure 11.

The new trucks are fuelled by green hydrogen generated by the electrolysis of water using an off-grid solar system. On-board, a 0.8 MW hydrogen fuel cell provides power and charges 1 MWh batteries, topped up by regenerative braking – see Figure 12. A demonstration truck was reverse engineered from an existing one, stripped of its diesel engine, by a specialist systems engineering firm.

Anglo-American, a mining company, had to integrate both energy supply and equipment design into its own operations, highlighting the lengths the company had to go to overcome lock-in to its existing supply arrangements. The lessons learnt from overcoming this lock-in may help the business become more agile.

The lock: Equipment manufacturers, maintenance and operations teams are locked into the paradigm of using diesel fuel

A solution: Work with a third party to create a tangible demonstrator so as to increase the confidence of incumbents

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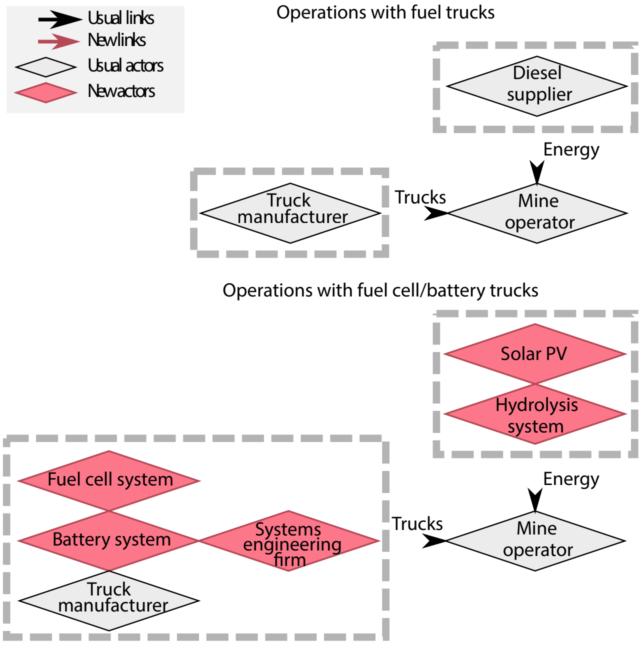

Figure 12: New supply arrangements for shifting away from diesel mining trucks

Lessons about Unlock

Historical Lock-in

Key Points: A valuable design exercise to avoid historical lock-in is to imagine production routes from a blank slate. Although such routes may never be implemented, they provide a lens through which to see possible future constraints, which may otherwise be hidden.

Avoiding historical lock-in is not easy as the future is unknown. Nonetheless, at relatively short time horizons, 10-15 years, it is generally possible to extrapolate from current trends and, over longer time horizons, to use scenario planning to explore different potential futures and to allow for non-linear change. This, however, requires a team of in-house experts responsible for tracking their developments across their industry, and mapping them to the future.

Another view of historical lock-in is the cost of the evolution of design and/or tools over multiple generations. Every time a design is changed, or new tooling introduced to the production line, or new subcontractors brought into the supply chain, the incentives to make use of these specific capabilities in future iterations of the product will grow. This is a special case of the sunk cost fallacy: It is of course cost efficient to make use of readily available capacities, but this may prevent better designs from being chosen or close off whole avenues of development if some capabilities become central to the identity of a firm.

Informational Lock-in

Key Points: Design cycles can be very short, with little time to investigate all the possible options. Optimisation tools can be developed and used to process information and explore the design space more fully. Even if the recommended solutions cannot be fully implemented, they can be used to inform a path of iterative change towards better solutions.

Informational lock-in is due to not being aware that changes are possible. This can arise from short development cycles, entrenched habits in the design of products, or insufficient awareness of new technological developments. It is particularly difficult to break out of this type of lock-in because it does not make itself apparent. It is further entrenched by the tendency of firms to recruit people with similar profiles to their existing staff; the resultant lack of diversity can create organisational blindness that locks designs into local optima.

To avoid informational lock-in, firms can devote part of their resources to research and development, but require, as part of the research process, regular reviews of the state-of-the-art as well as exploratory studies. The results of these reviews should then be communicated widely within the companies so that new good practices can spread. Because many of these changes will not be possible at any specific point of the product cycle, dedicated teams must take them up, and design integration strategies over future cycles. Continuous research towards globally efficient solutions should be encouraged. Not with the objective of implementing them, but to chart paths towards them. This can further help avoid future historical lock-in.

Informational lock-in may not be caused by a lack of knowledge, but rather a lack of process or cultural factors that would support use of that knowledge. For example, a structural engineer may be capable of designing a better structure, but the number of possible options is large, and therefore it is impossible for the engineer to improve the structure in the time available. To break out of this type of lock-in requires new types of tools or fundamental rethinking of the design cycle.

Construction gives a good example: Every building is different, if only because its site differs, and so the design of each one is unique. Designing a very complex product in a short time frame is the specialty of the construction industry, and this is done through extensive use of heuristic approaches and re-use of previous designs. Consequently, it is very uncommon that any building will be highly optimised for the purpose of lower embodied carbon, even though lighter buildings are universally understood as being better from an engineering standpoint.

A technological solution is the use of a computer modelling tool to generate large numbers of preliminary ('scheme') designs which help the project team make the right decisions early in the design process, and show material efficiency trade-offs that would otherwise remain

hidden. Materials make up a large fraction of the cost of the frame of a building, and nearly 4% of the overall project cost. Consequently, material saving can easily offset any supplementary engineering cost.

Use of scheme designs is more applicable to industries in which the processes are fairly standardised, and there are well-understood rules for the design. In such instances, the modelling tool reveals the complete set of options which match the prescribed rules with enough detail that the generated solutions can be used as starting points for designers. Use of scheme designs is at its most effective when a new platform is required. Their use avoids the trap of evolutionary change, wherein - possibly unintentionally - much of the previous product platform might be kept.

Coordination lock-in

Key points: Coordination is critical to effecting change but can only occur when there is mutual trust and cooperation within existing supply chains. Technology roadmaps can help to build a shared vision for future developments. Vertical integration can help to align interests with suppliers. If significant change is blocked by existing players then it may come from outside players, causing greater disruption.

Coordination is a critical issue in effecting change. It requires multiple actors with possibly diverging objectives to work together in a timely fashion to accomplish an objective. The potential for change within supply chains is constrained by existing power structures. Actors may oppose change that is not in their interest however, if they persist in blocking change they may become susceptible to disruptive change from new entrants.

Within a sector, publishing roadmaps can help. For example, in semiconductors, the performance goals of major manufacturers are known years in advance, and therefore devices can be designed assuming future products that only exist virtually. These roadmaps also drive all the supply chains to improve their products to match the future requirements.

Coordination problems also suffer from a scale barrier. The number of interactions which needs to be solved grows to the square of the number of actors needed to effect the change. Therefore, if for three actors to coordinate, three relationships need to be established, this number grows to 12 with four actors and 20 with 5. When any failed relationship can sink a project, large-scale changes which are not slowly phased in have a lower probability of success.

APPENDIX

Modelling change

The following figures attempt to map the difficulty of changing between two organisations. The vertical axis is used to locate the current situation, and the horizontal one the expected situation after the change. These maps can give a sense of what type of changes, or what combination of factors may lead to more difficult situations.

To generalise the lessons from each case study, we have abstracted the difficulty to change a production set-up to a number of simple factors: the number of actors in the chain and the over-capacity of the actors. Further, we looked at two important circumstances: whether, or not, the tools or suppliers can change their production process.

For example: The construction industry falls far behind the performance that it could achieve by deployment of state-of-the-art practices and technologies; it has high over-capacity. Counter-intuitively, an industry closer to the state-of-the-art tends to find change easier: the areas where the capacity stays the same or grows are lighter, indicating easier change.

The model

The manufacture of a product is modelled as the sequential addition of 'ingredients'. When the sum total of provided ingredients matches or exceeds the requirements of the product, the supply chain 'works'.

Working supply chains are then subject to a shock: the requirements for the product change, either because a completely new ingredient is required, or the balance of ingredients changes, or the amount of input is modified. The model then looks to find a new 'working' chain by increasing the capacity of the existing actors, adding new actors and reorganising the chain. It does this randomly, and the number of attempts is recorded. The more attempts needed to find a new working solution, the greater the difficulty of the transition.

The landscape of lock-in

We created a set of synthetic problems to represent the large number of possible transitions in response to shocks in the supply chain. We then modelled ease of transition in response to these problems. Figure 13 shows results with the dark zones representing difficult transitions and the light ones easier.

If the suggested process change maps onto darker areas of the graph, then there is a high risk that the change will be confounded by lock-in.

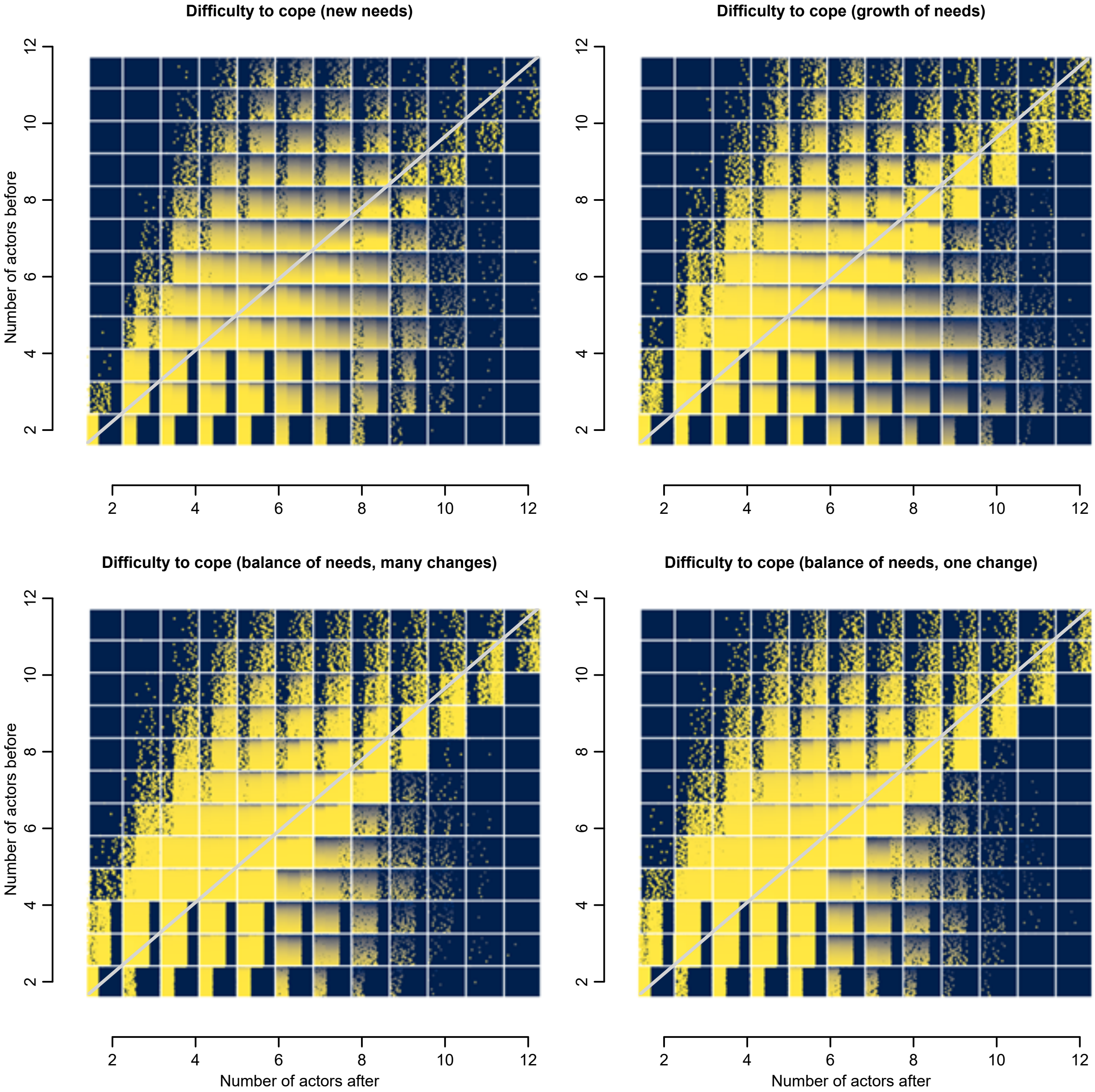

Figure 13: The graphs were created by considering the millions of possible transitions in response to a shock in the supply chain; each graph is for a particular type of shock, shown in the title. On the vertical axis is the capacity before the transition, and on the horizontal, after. The colour shade indicates the difficulty of the transition, darker is harder. Zones with few points are where very few successful transitions occurred. The y=x line marks transitions where there was no change in the production set-up, i.e. no additional capacity.

References

1. Material Economics. *Industrial Transformation 2050 - Pathways to Net-Zero Emissions from EU Heavy Industry*.; 2019. https://materialeconomics.com/latest-updates/industrial-transformation-2050.
1. Department for Environment Food & Rural Affairs. *Our Waste, Our Resources: A Strategy for England*.; 2018. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/765914/resources-waste-strategy-dec-2018.pdf.
1. Dunant CF, Drewniok MP, Sansom M, Corbey S, Cullen JM, Allwood JM. Options to make steel reuse profitable: An analysis of cost and risk distribution across the UK construction value chain. *J Clean Prod*. 2018;183:102-111. doi:10.1016/j.jclepro.2018.02.141
1. Horton PM, Allwood JM. Yield improvement opportunities for manufacturing automotive sheet metal components. *J Mater Process Technol*. 2017;249:78-88. doi:10.1016/j.jmatprotec.2017.05.037
1. Horton PM, Allwood JM, Cleaver C. Implementing material efficiency in practice: A case study to improve the material utilisation of automotive sheet metal components. *Resour Conserv Recycl*. 2019;145:49-66. doi:10.1016/j.resconrec.2019.02.012
1. IEA. *World Energy Balances: Overview*. Paris; 2020. https://www.iea.org/reports/world-energy-balances-overview.
1. Crowson P. Mine size and the structure of costs. *Resources Policy*. 2003;29(1-2):15-36. doi:10.1016/j.resourpol.2004.04.002
1. Office of Energy Efficiency and Renewable Energy (EERE). *Mining Industry Energy Bandwidth Study*.; 2007. https://www.energy.gov/sites/prod/files/2013/11/f4/mining_bandwidth.pdf.
1. Duffy K-A, Valery W, Jankovic A, Holtham P. Integrating Bulk Ore Sorting into a Mining Operation to Maximise Profitability. In: *Proceedings MetPlant 2015*. ; 2015:273-287.

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