Handprints of Product Innovation:
A Case Study of Computer-aided Design in the Automotive Sector

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Abstract: The production of every product creates "footprints": unintended negative consequences for the environment and human health. However, product-related innovation can also bring "handprints": beneficial changes to "business as usual," measured in the same units as, and directly comparable with, footprints. Any entity that shrinks its footprints while also growing its handprints can eventually become NetPositive. As a company that seeks both to reduce its footprint and to grow its handprints, Dassault Systèmes is researching its potential to create environmental and human-health handprints by leveraging 3D technology. We investigate to what extent recent application of 3D technology within the automotive industry, such as computer-aided product design and testing, has created significant handprints in relation to climate and other impacts. We quantify handprints for a set of innovation-specific cases using scoping life cycle assessments and find carbon handprints which range from 4 thousand to 30 million metric tons of CO_2 equivalent. We then extrapolate these results to estimate the full handprint creation potential for computer-aided innovation within the automotive sector. We find a range of 300-600 million metric tons of CO_2e in handprinting potential for the automotive sector from now to 2020. And we note that, as shown in the case studies presented here, the innovations would bring benefits for many other impact categories as well, including human health, fossil energy depletion, and ecosystem impacts.

Introduction to Handprint-Based NetPositive Accounting

Most human activities and all modern human lives require the use of goods and services. Production of each of these goods and services generates negative impacts, such as pollution and the consumption of natural resources. And each production process in turn requires the use of other goods and services from other production processes, creating supply chains that span the economy and the globe. Each process in these supply chains in turn generates its own negative impacts. We call the sum of these negative impacts from a production process and its vast supply chain the "footprint" of producing the good or service. Since the impacts are multi-faceted, so are the footprints. Every product has a "Carbon footprint" measuring the greenhouse gas emissions, a "water footprint" measuring water consumption, and so-on. And if every product has footprints, so does every person and every organization. While we can and must work to continually reduce them, we will never drive our footprints to zero. Sustaining a person and operating an organization inevitably causes harm, albeit unintended.

Like most companies, Dassault Systèmes produces footprints. As a leading software developer of a 3DEXPERIENCE platform that leverages such technologies as computer-aided design (CAD) modeling, simulation, manufacturing, and product lifecycle management, large sources of the carbon footprint at Dassault Systèmes include electricity use and air travel at its facilities. The company also creates footprints on other indicators, such as significant electronic waste that it endeavors to manage responsibly, but this study will focus on carbon footprints associated with greenhouse gas emissions.

The inevitability of footprints does not mean that every person and every organization is doomed to be "bad news" for the planet and future generations. These same people and organizations can also bring positive change, benefits, healing to the world around them. We call footprint-consistent estimates of the impacts of positive change *handprints*. By shrinking their footprints while also growing their handprints, a person or an organization can eventually do more good than harm, becoming NetPositive.

Dassault Systèmes has put into place measures to reduce its carbon footprint, such as telepresence and videoconferencing capabilities to reduce air travel. However, its full scope of potential positive impact derives from its core business. Its 3DEXPERIENCE platform is used to create "virtual universes" in which products are designed, simulated, and manufactured, in industries such as aerospace, automotive, industrial equipment, high tech, natural resource management, and the life sciences. As such, its potential to reduce the impacts of these products, and thus enable customer handprints, is very large. The company is a founding member of the SHINE research program in part to determine how best to enable the global transformation to sustainability: either by investing in further footprint reductions, or by further developing its handprint-enabling software technologies to generate positive impacts in its customer base, in its bid to become a NetPositive company.

Methods for handprint-based NetPositive assessment are described in detail elsewhere.[1],[2] Here we summarize a few basic aspects of the method which are essential to understanding of the case study applications which follow.

HBNA takes the full life cycles of products into account. No part of a life cycle affected by a change or decision is out of scope – indeed, no impact caused by an actor is out of scope. That said, the scope of *footprint* assessment in HBNA consistently focuses on what is called the cradle-to-gate portion of product lifecycles. This is in contrast with the less consistent scope definition used in footprint assessment to date, before the advent of handprint assessment. In pre-HBNA footprinting practice, footprint scope is defined as being cradle-to-gate, except when it needs to include the use phase and/or the end-of-life phase. The need to expand the scope to is then established on a standard-by-standard basis in a sector-specific way; for example the GHG protocol for carbon footprinting calls for inclusion of the use phase if the product consumes energy during its use phase, but not if use of the product influences the energy use of some other product or process. We understand that without handprints, the above approach seemed like the only way to encourage companies for making progress on the use phase impacts of their products, but we also note that this approach is both inconsistent and incomplete. In HBNA, a consistent and logical cradle-to-gate footprint scope poses no problems of incompleteness because the scope of handprinting always includes direct and indirect influences across the scope of the total life cycle.

In handprint-based NetPositive accounting, we define the footprint of an entity in a way that is logically consistent across all cases: the sum total of the negative impacts caused by all the processes needed to sustain and enable that entity to offer what it does to the world. For a company or organization, this can be referred to as the sum total of the negative impacts caused in order to enable that organization to operate and perform its mission. In life cycle assessment (LCA) parlance, this is the "cradle-to-gate footprint" for the entity. And in GHG protocol parlance, this is the Scope 1 + Scope 2 plus Scope 3 upstream footprint. Notice that the footprinting system accounts for two ways that consumers and producers influence the world: by causing direct impacts through their own operations, and by causing indirect impacts via purchasing from other producers.

We define the handprint of an entity as the **footprint-consistent impacts of changes caused by the entity, relative to what would have happened without the entity being an agent of change.** The handprint of an entity is the net change brought about by that entity – hopefully but not necessarily positive or beneficial – measured in the same impact units as used in footprinting. The scope of the system includes any and all causal pathways by which the causes changes in impacts. Thus, one such set of pathways is the same set of pathways included by footprinting: direct impacts of operations, and indirect impacts via purchasing from other producers. Handprint system scope also includes other, equally impactful ways that companies and production can exert influence on the world. In so doing, it opens up a wider realm of pathways for positive influence. While footprinting encourages us (holds us responsible) to reduce the impacts occurring in our supply chains, handprinting encourages us to be a cause of positive change anywhere and everywhere in the world, both within and outside of the life cycles of the goods and services that we produce and consume. In HBNA, we refer to this broader set of impact-generating influences "ripple effects." If a company makes the use phase of its product more (or less) efficient, the impacts of this change are part of its handprint. If the company uses information flows to affect how its own or other products are used, or managed at their end-of-use, these impacts are part of its handprint. Information can inspire, inform, encourage, or enable change.

Notice that just as commerce stimulates more commerce in supply chains, positive ripple effects can stimulate more positive ripple effects in the world too. For example, let's say an entity encourages some customers to co-create handprints, by using their product more efficiently. If this initial encouragement leads these customers to get active in creating other handprints, those are part of its ripple effect. And if their handprinting stimulates other people and companies to get involved in handprinting, their positive influence spreads further.

Note that, by including influences of the company anywhere in the world, including the life cycles of its products, HBNA holds companies accountable for both positive (and negative) changes which they may make to the use phase and end of life impacts of their products, whether these bring changes to direct impacts of their own product life cycles, or changes to the impacts of the life cycles of other products. For this reason, the HBNA framework is more comprehensive than the original footprinting-only frameworks, *and* it is able to operate with a single, stable, logical and consistent definition of footprints. Footprints are the impacts caused by enabling the entity to live or operate, and handprints are the impacts of the changes that entity causes in the world while operating.

There are two ways to create a handprint:

- Preventing/avoiding footprints that would otherwise have occurred (this includes reducing the magnitude of footprints that occur, relative to what their magnitude would otherwise have been)
- Creating positive benefits which would not otherwise have occurred

It is helpful to use the shorthand term “business as usual” (abbreviated as “BAU”) to refer to “what otherwise would have occurred”. Using this, we can express the two ways for creating handprints as:

- Reducing total footprints relative to BAU
- Creating positive benefits relative to BAU

Product-related handprints for example can be created through a combination of the following interventions:

- Improving the life cycle performance of an *existing* product through innovation, so that future demand for the product is met by an improved solution rather than the pre-innovation solution.
- Introducing a *new* product which performs better than other product(s) on the market whose demand it displaces.
- Increasing demand for an *existing* product at the expense of demand for other product(s) on the market which perform worse than the subject existing product.

Handprints are created by changes that are voluntarily achieved – changes that would not happen without intentional and voluntary action on the part of the actor. Thus, reductions in product environmental footprints that are achieved in order to comply with regulations do not count towards handprints. Reductions which arise due to improvements which *go beyond* those required by law do qualify, in that the beneficial impacts of the “excess improvement” count toward handprints.

It is common for events to have multiple causes. In Handprinting we attribute handprints (and thus causation) to actors: individuals, to groups of individuals, and to organizations. Products can be instrumental in how the actors actually create change, but they are not cited as being direct causes themselves. Causers of a handprint are actors about whom we can say: the handprint would not have happened without their influence. The handprint that they cause becomes part of their total handprint.

Causers can be distinguished from enablers, about whom we can say: “it happened in part through the use of their product.” While enabling a handprint is not causing a handprint, enablers of handprint-creating actions can and do play an important role in the handprinting system. As a seller of products that may enable handprinting actions, they are in a position to benefit (by selling more product) by promoting the demand for handprinting. They may also be able to provide training or advice to users of their product in ways that *increase* their customers' handprinting activity, and if by doing so they can demonstrate that they have been a cause of this increase, they become handprint causers themselves, the handprint of the increase becoming part of their handprint. Finally, they may be able to redesign their product so that it becomes a more effective enabler of handprinting; if there is a resulting increase in the amount of handprinting that occurs, directly attributable to the product redesign, this increase too becomes a handprint of the enabler-turned-causer.

Footprinting *attributes responsibility for a given impact to multiple actors*. For example: a steel producer's footprint includes all of the pollution from their factory. The footprint of car producer includes that portion of the steel producer's pollution which is attributed to producing the steel purchased by the car producer. The footprint of the car buyer includes one car's worth of the steel producer's pollution as well.

Thus, in Footprinting, we routinely say that many actors are *each* responsible for the same impact. This is *shared responsibility*.

Turning next to Handprinting, we again find shared responsibility; and since Handprint impacts are generally positive, we can call it *shared credit*. Every causer of a handprinting action can take credit for the positive impacts of that action as part of their handprint. Thus, the total Handprint of a set of actors can be less than the sum of their individual Handprints, *if* there is any overlap in their responsibilities – meaning, *if* their Handprints include any of the same unique events. As with Footprinting, accounting correctly for their shared Handprint is done by avoiding double-counting of the impacts of the same event, which can be done by preserving information about the uniqueness of each event, and counting the impacts of each event only once.

Time plays in important role in handprint-based NetPositive assessment, in three ways. First, to assess for NetPositive, we need to compare footprints and handprints created during the same period of time by an entity or group of entities. The most common time frame for assessing the footprints of organizations is annual. Thus, we adopt this same convention in assessing the Handprints of organizations and other actors, and in assessing whether these organizations and other entities are NetPositive. In this case, what we are assessing is whether the entity is NetPositive for that year, by generating a handprint that year which exceeds its footprint for that year. Other time frames are possible, of course.

Second, a product-related action often has consequences which play out over the life cycle of the product. For example, a home owner can install a water heater insulation blanket. The blanket will then save energy by reducing standby heat losses from the hot water tank, for as long as the blanket is in place. The question arises: when should the lifetime energy savings handprint of the water heater blanket be counted as a handprint for the actor: at the time (or during the year) when the blanket is installed, or year by year as the energy is saved? Both options are possible, and each has its particular advantages.

The first approach, counting the life cycle handprint all during the year of installation, is called the sales-year method. A primary strength of this method is its simplicity. The second approach, counting the impacts during each year in which they occur, is called the impact-year method. It has the advantage of being explicit about the actual timing of the expected impacts, which is particularly valuable for long-lived products. Making the timing explicit can be relevant for climate policy for example, and also in highlighting the potential influence of context variables in altering the actual handprint which occurs. As an example of the latter, the handprint of a long-lived product which will save electricity depends in turn on which fuel(s) will be used to generate the electricity during the life of the product, and this may change across the product life time.

Third, there is the question of the duration over which the influence of a change persists, in relation to business as usual. For example, when a product design is improved by innovation, the newly innovated product will often be sold for multiple years. How many years of sales of the innovated product can count towards the handprint of this innovation? Clearly more than one year of sales is affected, but also clearly, the product will eventually be retired and replaced by still newer products, either from the same company of from competitors. The "Innovation-Relevant Time Horizon", or IRTH, is the term we give to the duration of time over which sales of an innovated product contribute to the total handprint of the innovation. We suggest that the proper value for IRTH's will vary by product type, and will be shorter for product types for which innovation cycle times are shorter.

As noted above, one of the ways to create a handprint is by improving the life cycle performance of an *existing* product through innovation, so that future demand for the product is met by an improved solution rather than the pre-innovation solution. This is the form of handprint creation on which we focus in the analysis that follows.

We began by reviewing publicly available documentation about vehicle-specific innovations published by Ford,[3] selecting those innovations for which enough data and information were provided to enable what life cycle assessment researchers term a "scoping LCA" of the innovation. A scoping LCA takes a simple description of a product or a set of alternatives or scenarios, and uses this description to build a quantitative model of the product or alternatives, linking to secondary data for models of the impacts of the supply chains of each input to the final model. In the assessments presented here, we used the Ecoinvent database[4] as our source of secondary data on the impacts.

We focused on examples published by Ford, although our intent is to conduct an analysis that ultimately assesses the potential for handprinting in the automotive sector in general. Restricting our search to examples published by a single company such as Ford has the benefit of narrowing scope, and also capturing the range of innovations which at least one company has chosen to undertake and publicly document recently. Ford has the added benefits that it has undertaken a number of high-profile innovations recently, including lightweighting of the F-150 pickup truck. Ford continues to extensively apply 3D technology to innovate a variety of its products.[5]

The following innovation cases were found to provide enough detail that we could build and use simple scoping LCAs of the scenarios pre- and post-innovation, in order to identify whether a handprint was achieved by the innovation, and if so to generate an order-of-magnitude estimate of the handprint for different environmental impact categories.

Table 1: Summary of vehicle handprinting innovations assessed

Vehicle lightweighting	
Lincoln MKT Crossover	Tailgate made 20 lbs lighter, substituting Mg and Al for steel
Ford F-150 Truck, 2015 compared to 2014	700 lb overall weight reduction, largely from shifting from steel to aluminum throughout.
Ford Transit Van replacing E-series Van	Extensive use of lighter, high-strength steel improved fuel economy by 25% and increased capacity by 300 lbs.
Vehicle aerodynamics	
Ford Escape, Fusion, and Lincoln MKZ	Aerodynamic drag reduced in 2013 models by 10 percent compared to 2012 models, via measures including Underbody shielding, tire spoilers, wheels, body shape, vehicle proportion, Active Grille Shutters and optimized aerodynamics of wheel and mirror design

Product-related innovation handprint assessments take the full life cycle of the product into account:

$$\text{Handprint} = F_b - F_n \qquad (1)$$

where

F_b is the Business-as-usual footprint of the product over its lifecycle, and

F_n is the New Footprint of the product over its life cycle

In building our assessments, we divide the life cycle of the vehicles into four phases: upstream (cradle-to-final-production), final production, use, and end-of-life management. For each phase, we model just that portion of the product systems' life cycle scope that has been changed by the innovation. Thus, for example, in the case of the lightweighting of the tailgate of the Lincoln MKT Crossover, for the upstream phase, we model just the material inputs to manufacturing the tailgate, before and after the innovation.

In some of the Handprinting case studies that we perform in the SHINE research program, we have access to detailed life cycle assessment data on the innovated products, before and after the innovation, which greatly facilitates estimation of the handprint of the innovation, and increases the precision of the results. In the case studies presented in this paper, we do not have access to information from the manufacturer other than brief published descriptions of the innovations. In such a data-sparse context, we make conservative assumptions throughout the analyses, and we present the results in the spirit of order-of-magnitude estimates of the innovation handprints, rather than calculations precise to the third significant digit. Order-of-magnitude estimates are appropriate because the purpose of these assessments is to provide an estimate of the potential for design-based handprinting within a selected industry, and to illustrate application of the handprinting assessment framework at this scale. In this application, the order-of-magnitude assessment of the potential handprints associated with design-based innovations in the automotive sector will form the basis of a recommendation to Dassault Systèmes for potential handprint enablement in one of its critical customer segments.

For each case, we need the following information in order to estimate the handprint of the innovation:

- An estimate of the material (and if relevant, energy) inputs to vehicle manufacture which are affected by the innovation
- An estimate of how the use phase of the vehicle is affected by the innovation (e.g., changes to fuel economy, durability, maintenance requirements)
- An indication of whether or not end-of-life management (e.g., recycling) would be affected by the innovation.
- Estimated lifetime vehicle mileage
- A value for the Innovation Relevant Time Horizon (IRTH) relevant for automobiles.
- Forecasts of annual sales for the innovated vehicle throughout the IRTH.

Regarding end-of-life management, none of the innovations appear to adversely affect recycling of vehicle materials at end of life: most reductions in the use of one metal are replaced by the use of lighter, higher strength alloys, and the bulk of the innovations involve reduction in overall material used per vehicle. So we assumed no changes to end-of-life impacts for any of the innovation cases.

Regarding the use phase, each of the above innovations generates its positive impact by improving fuel economy of the vehicle. For the bulk of the lightweighting innovations, the only quantitative impact information provided was the vehicle weight reduction. In these cases, we obtained published pre-innovation curb weights for the vehicles, and used these together with the weight reduction information to calculate a percentage weight reduction for the vehicle, relative to pre-innovation weight. We then use the innovation-specific weight reduction percentage together with an extremely conservative weight-fuel economy relationship of 6% fuel economy improvement per 10% weight reduction for cars, and an 8% fuel economy improvement per 10% weight reduction for light trucks [6], to estimate what is likely to be a lower-bound estimate on the full benefits of the lightweighting innovations. We then compare the total fuel economy impacts of all modeled innovations for the vehicle to the reported time series data on fuel economy for the selected vehicle provided by the US Department of Energy[7] to ensure that estimated lightweighting-related innovation impacts do not exceed total reported gains in fuel efficiency.

Lightweighting of vehicles can bring significant benefits to fuel economy, partly because of systemic impacts in vehicle design that further amplify the direct benefits of reducing vehicle weight. For example, when weight is reduced, the motor and powertrain can be downsized while preserving the same acceleration performance as before the lightweighting, leading to further gains in fuel economy. This is why Cheah et al (2010) cited a figure of 6% increase in fuel economy for cars and 8% increase for light trucks associated with a 10% weight reduction. As they also noted, while in the past lightweighting has often been used to increase acceleration performance, in the future we can expect that increasing amounts of the benefits of lightweighting (and other vehicle innovations that can affect efficiency or performance) will accrue to fuel economy rather than further increases in acceleration performance.

As described in Norris (2015), a handprint-generating innovation may make the product more attractive to buyers for one or more reasons such as better performance, lower purchase price, lower the total cost of ownership, and/or improved (reduced) environmental footprint. This increase in attractiveness to buyers may in turn bring an increase in market share for the product. If the product has a lower cradle-to-grave footprint than the products negatively impacted by the shift in market share, this factor will increase the total handprint accruing to the innovation. In this paper, we conservatively assume no displacement of higher-footprint products via increased market share driven by the innovations.

For an innovation-relevant time horizon (IRTH) we use a figure of 5 years in this paper. Thus, we credit each of the innovations with impacting the life cycle impacts of vehicles sold over 5 years following the innovation. Although in actual fact, the innovation may influence the performance of vehicles sold after the fifth year, the implicit (and conservative) assumption is that it would have been introduced anyway after 5 years due to pressure from competing products in the marketplace.

For total miles driven in the use phase of the cars affected, we use the combined data points of 12,928 average miles driven per year per vehicle from the most recent Transportation Energy Data Book[8], and 11.4 years as the average age of cars on the road in the US, from RL Polk. The resulting expected lifetime mileage per vehicle is 147,400 miles. We use vehicle-specific fuel economy data and curb weight data for the base year of the innovation. Together, the data described above are used to obtain estimates of fuel consumed over the vehicle life, before and after the innovation.

We estimate total “cradle-to-gate” the environmental impacts of vehicle fuel consumption using data from the Ecoinvent database for the combustion of 1 gallon of gasoline in a typical modern European sedan. These impacts account for the emissions from the vehicle as well as environmental impacts of the full supply chain required to extract and refine crude petroleum and distribute the fuel to point of use.

Case-Specific Results

For each impact category, there are impacts that occur in the year of production, and impacts that occur and accumulate across the vehicle life. The impacts in the year of production are those of changes to the materials and energy needed to manufacture the vehicle, including the impacts of the full supply chains of all of these altered inputs to final manufacture. These impacts are labeled “upstream” in the graphs below. The impacts that occur and accumulate across the life cycle are those which arise from innovation-driven changes to the use phase, which in these cases arise due to improvements in vehicle fuel economy.

The footprints or negative impacts of vehicle production and use both before and after innovation have the dynamic character described above. The handprint of the innovation arises as the difference between pre-innovation and post-innovation impacts, so it has the same dynamic character. The graph below shows cumulative handprints on an annual basis, indicating how these handprints unfold over time. The curves all rise linearly with time, as the handprints of each year’s fuel economy benefits accumulate.

Handprints can be calculated for each impact category. In the results presented below, we have applied the US EPA’s TRACI 2.1 methodology for Life Cycle Impact Assessment. As shown in Table 1, the results for each impact category are calculated in different units. For this reason, in order to display them on the same graph, we need to normalize the handprint results in some way. In the graphs below, we obtain normalized results by dividing the handprint results by the absolute value of the upstream handprint. The upstream handprint is given by the difference between the pre-innovation upstream footprint and the post-innovation upstream footprint:

$$\text{Handprint\_u} = F_{b\_u} - F_{n\_u} \tag{1}$$

where

F_{b_u} is the Business-as-usual or pre-innovation upstream Footprint, and
F_{n_u} is the New or post-innovation upstream Footprint

Lincoln MKT Tailgate Lightweighting

We normalize using the absolute value of the upstream handprint because in some cases – indeed, for all but two of the ten TRACI impact categories – the upstream handprint is negative, meaning that the innovation leads to larger upstream impacts than before the innovation occurred. This is why most of the lines for normalized results in the graph begin at -1. For two impact categories – Ecotoxicity and Human Health Cancer – the innovation brings upstream benefits as well, so the cumulative normalized handprint curves for these impact categories start at 1. A cumulative normalized handprint curve crossing through zero means that the negative upstream innovation effects have been compensated by cumulative use phase innovation effects by the year in which the crossover occurs. For all but one impact category (Human Health, non-Cancer) the cumulative handprint becomes positive (beneficial) by the end of the vehicle life. Global warming impacts, for example, become positive in year 3.

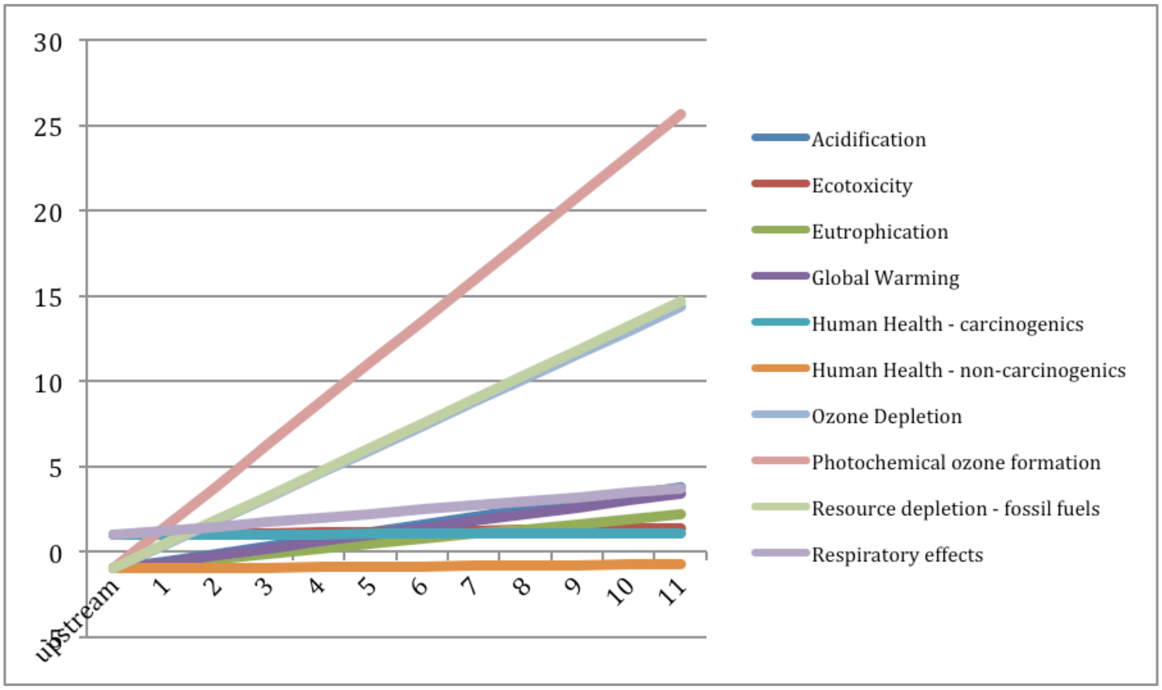

Figure 1: Cumulative handprints normalized by absolute value of upstream, Lincoln MKT Tailgate Lightweighting

Ultimately, the size of the total handprint achieved by the innovation depends on how many vehicles are sold during the innovation-relevant time horizon. Based on historical sales data for the Lincoln MKT, we project annual post-innovation sales of 5000 vehicles per year. Based on this projection, the total handprint results for MKT tailgate lightweighting, by impact category, are summarized in Table 2. We have rounded the results to two significant digits, to avoid conveying false precision in the results, since parameters such as annual sales are forecasts and the upstream results are based on a scoping LCA. The climate handprint of Lincoln MKT tailgate lightweighting is estimated to be on the order of 4 kilotons of CO_2 equivalent.

Table 2: Total life cycle handprints for the MKT Lightweighting Case

Impact category	Unit	Per vehicle	Total
Acidification	kg SO_2 eq	0.32	8,000
Ecotoxicity	CTUe	240	6,100, 000
Eutrophication	kg N eq	0.078	2, 000
Global Warming	kg CO_2 eq	160	3,900, 000
Human Health - carcinogenics	CTUh	2.3E-05	0.6
Human Health - non-carcinogenics	CTUh	-6.0E-06	-0.2
Ozone Depletion	kg CFC-11 eq	3.4E-05	0.9
Photochemical ozone formation	kg O_3 eq	4.3	110, 000
Resource depletion - fossil fuels	MJ surplus	360	9, 000,000
Respiratory effects	kg PM2.5 eq	0.048	1,200

Ford F-150 Pickup

The lightweighting of the Ford F-150 pickup between model years 2014 and 2015 is probably the most emblematic of all of the handprinting innovations addressed in this paper. As noted in Table 1, a comprehensive structural material redesign enabled a roughly 700-pound overall weight reduction, largely by shifting from steel to aluminum. As shown by federal fuel economy data, the resulting increase in fuel economy is on the order of a shift from an average figure of 18 miles per gallon (mpg) to 20-21 mpg for a similar vehicle configuration, an increase on the order of 15%. With a 2015 vehicle curb weight of roughly 4200 pounds for a regular cab, V-8 model, the 700 pound weight drop represented an approximately 14% decrease in weight relative to 2014. Applying the benefit ratio for fuel economy from weight reduction described earlier yields a corresponding 11% improvement in fuel economy attributable to lightweighting.

To model the upstream impacts of the innovation in the absence of actual bill of materials data or life cycle assessment results, we note from the Ecoinvent database that roughly 80% of the mass of a similar vehicle is metal, with 92% of the metal mass being different forms of steel, and 5% of the metal mass being aluminum. The F-150 frame weight went from 23% aluminum to 77% aluminum, resulting in a weight reduction of roughly 25 pounds. The density of aluminum is 2.7 tons per cubic meter, compared with 7.6 tons per cubic meter for low alloyed steel. Based on these data points, together with a pre-innovation curb weight of 4900 pounds, and an assumption that the pre- and post-innovation masses of materials other than aluminum and steel remain unchanged, we model the overall 700 pound weight reduction as a replacement of 3577 pounds of steel plus 245 pounds of aluminum with 2072 pounds of steel plus 1050 pounds of aluminum.

As for the other cases, we normalize using the absolute value of the upstream handprint. For one of the impact categories –Human Health Cancer – the innovation brings upstream benefits as well, so the cumulative normalized handprint curves for these impact categories start at 1. A cumulative normalized handprint curve crossing through zero means that the negative upstream innovation effects have been compensated by cumulative use phase innovation effects by the year in which the crossover occurs. For eight of the ten impact categories the cumulative handprint becomes positive (beneficial) by the end of the vehicle life. Global warming impacts, for example, become positive during the 3rd year of product use.

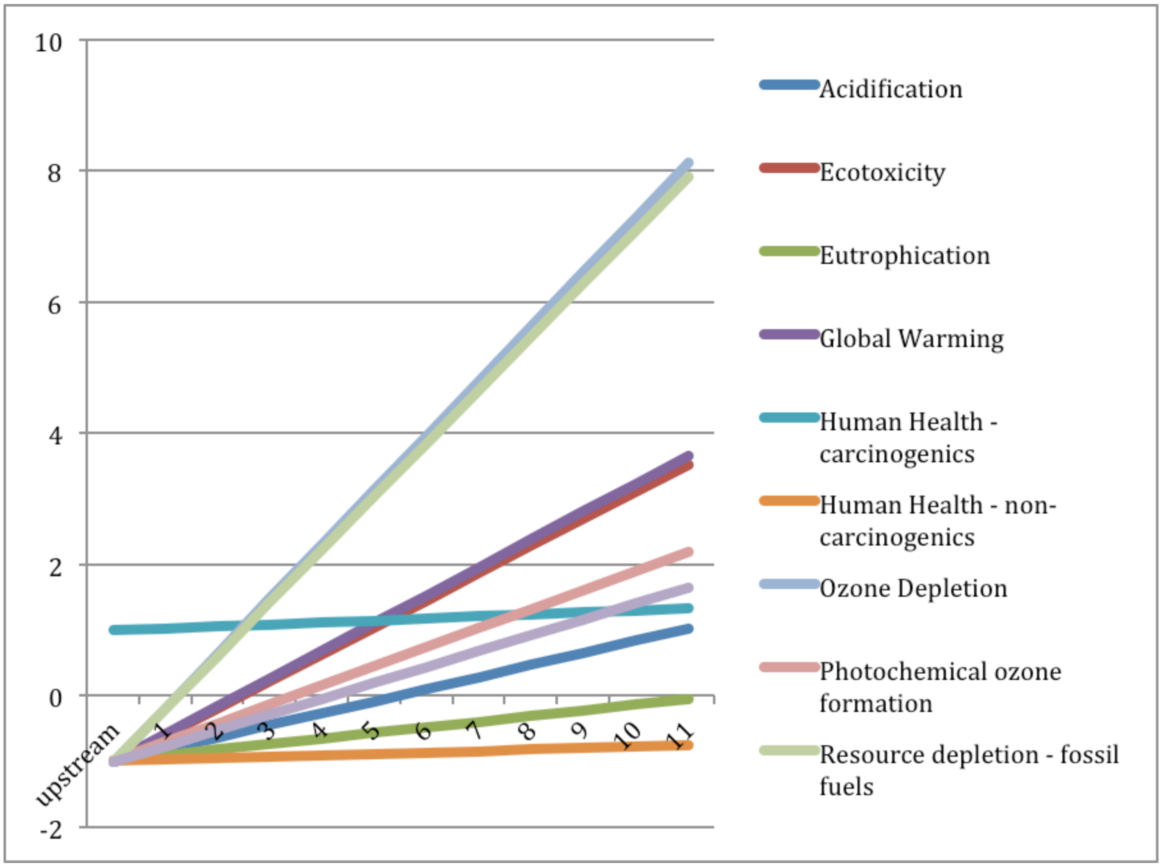

Figure 2: Cumulative handprints normalized by absolute value of upstream, Ford F-150 Lightweighting

The size of the total handprint achieved by the innovation depends on how many vehicles are sold during the innovation-relevant time horizon. Based on historical sales data for the F-150, we conservatively project average global annual post-innovation sales of 800,000 vehicles per year during the innovation-relevant time horizon. Based on this projection, the total handprint results for F-150 lightweighting, by impact category, are summarized in Table 3. We have rounded the results to two significant digits, to avoid conveying false precision in the results, since parameters such as annual sales are forecasts and the upstream results are based on a scoping LCA. The climate handprint of F-150 lightweighting is estimated to be on the order of 30 million tons of CO_2 equivalent.

Table 3: Total life cycle handprints for the Ford F-150 Lightweighting Case

Impact category	unit	Per vehicle	Total
Acidification	kg SO_2 eq	10	40,000,000
Ecotoxicity	CTUe	2621	10,000,000,000
Eutrophication	kg N eq	-0.13	-530,000
Global Warming	kg CO_2 eq	7500	30,000,000,000
Human Health - carcinogenics	CTUh	0.0002	1000
Human Health - non-carcinogenics	CTUh	-0.0004	-1,500
Ozone Depletion	kg CFC-11 eq	0.0016	6,000
Photochemical ozone formation	kg O_3 eq	149	600,000,000
Resource depletion - fossil fuels	MJ surplus	16274	65,000,000,000
Respiratory effects	kg PM2.5 eq	1.1	4,300,000

Ford Transit Connect Van

Ford reports that through extensive use of lighter, high-strength steel, it was able to boost fuel economy by 25% and increase capacity by 300 lbs for its Transit Connect van, relative to the E-Series van. An advantage of this case is that the fuel economy benefits are reported explicitly and do not need to be derived from weight reduction figures. A major weakness of this case however is that no data are given regarding the material shift – mass and alloys used (and any secondary bill of material consequences) before and after the innovation.

The weight reduction required to achieve a fuel economy improvement of 25%, including the systemic benefits of weight reduction (allowing down-sizing of the power train for example) would be on the order of 30%. The carbon footprint (in kg CO_2 equivalent) of steels in the Ecoinvent database range by a factor of 10 per kg of steel, depending on recycled content, steel-making process, and alloys. Also in the Ecoinvent database, the rough bill of materials for a generic van consists of 75% steel by mass. The curb weight of a current Ford Transit van is 1724 kg. If we assume that the initial van design was indeed 75% steel by mass, and that a 30% weight reduction is entirely in the form of reduced steel mass, we arrive at estimated steel mass in the vehicles before and after innovation of 1850 kg and 1100 kg, respectively. In order to estimate the upstream impacts of the innovation, for pre-innovation steel we select EAF steel, un- and low-alloyed; and for post-innovation steel we select EAF chromium steel.

As in the other cases, we normalize using the absolute value of the upstream handprint. A cumulative normalized handprint curve crossing through zero means that the negative upstream innovation effects have been compensated by cumulative use phase innovation effects by the year in which the crossover occurs. For five of the ten impact categories the cumulative handprint becomes positive (beneficial) by the end of the vehicle life. Global warming impacts, for example, become positive midway through the estimated lifetime. These results are also quite conservative because the estimated miles traveled per year is probably lower than actual, since it is based on personal automobile use rather than commercial van use.

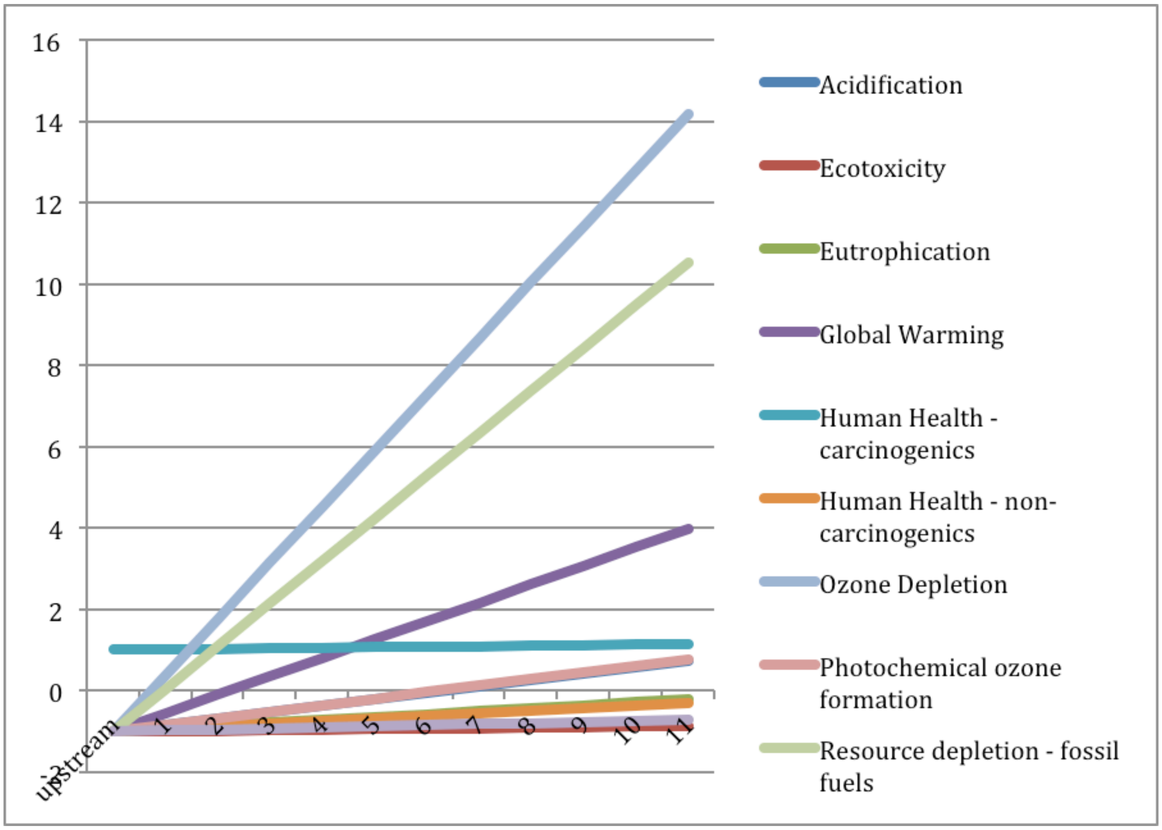

Figure 3: Cumulative handprints normalized by absolute value of upstream, Transit Van Lightweighting

The size of the total handprint achieved by the innovation depends on how many vehicles are sold during the innovation-relevant time horizon. Sales of the Transit Van have been rising significantly and steadily over the past 5 years, from 27,000 sold in the US in 2010 to 43,000 in 2014 and a projection near 50,000 for 2015. We somewhat conservatively assume sales volumes of 50,000 per year during the innovation-relevant time horizon. Based on this projection, the total handprint results for Transit van lightweighting, by impact category, are summarized in Table 4. We have rounded the results to two significant digits, to avoid conveying false precision in the results, since parameters such as annual sales are forecasts and the upstream results are based on a scoping LCA. The climate handprint of transit van lightweighting is estimated to be on the order of 14 tons per vehicle, or 3.6 million tons of CO_2 equivalent for full sales impacts over the 5-year IRTH.

Table 4: Total life cycle handprints for the Ford Transit Van Lightweighting Case

Impact category	unit	Per vehicle	Total
Acidification	kg SO_2 eq	16	4,000,000
Ecotoxicity	CTUe	-37607	-9,400,000,000
Eutrophication	kg N eq	-2	-537,000
Global Warming	kg CO_2 eq	14,000	3,600,000,000
Human Health - carcinogenics	CTUh	0.00097	240
Human Health - non-carcinogenics	CTUh	-9.3E-05	-23
Ozone Depletion	kg CFC-11 eq	0.0031	780
Photochemical ozone formation	kg O_3 eq	183	46,000,000
Resource depletion - fossil fuels	MJ surplus	31935	8,000,000,000
Respiratory effects	kg PM2.5 eq	-7.4	-1,800,000

Estimates of Sector-Wide Handprint Potential from Computer-Aided Automotive Design

In 2013, total US production of cars and light trucks for domestic use was 9.3 million and 5.1 million, respectively.[9] With an additional 18% of this production value added as production for exports, total US production of cars and light trucks was approximately 17 million.[10] Globally, total production that year was approximately 65 million.[11]

Based on the innovation-specific cases presented earlier, we note that for the F-150 alone, the climate handprint of the effects of vehicle lightweighting were approximately 7.5 metric tons of CO_2 equivalent per vehicle over its life. For the transit van, the climate handprint of lightweighting was conservatively estimated at roughly 14 metric tons per vehicle over its life. Note that in additional to lightweighting, computer-aided design is instrumental in driving other forms of innovation including improved aerodynamics.

To achieve a sense of the power of innovation-driven handprinting in the global automotive sector, let's take a range of 5-10 metric tons CO_2e as a reasonable estimate of the handprint potential per vehicle due to computer-aided design. Next we consider what pace of innovation is reasonable, given the economic pressures to sell a stable platform for a series of years. Innovation's impacts are felt in more than just one year of sales; they influence the design of vehicles sold for multiple years. In the assessments presented here, we adopted an innovation-relevant time horizon of five years. Adopting the innovation-relevant time horizon of 5 years, handprint-generating innovation can address the full global vehicle market if it is applied to 20% of the vehicle fleet per year over a 5-year period. These assumptions, applied to a stable global vehicle output of 60 million (conservative assumption), yields a range of 300-600 million metric tons of CO_2e in handprinting potential for the automotive sector from now to 2020. And we note that, as shown in the case studies presented here, the innovations bring benefits for many other impact categories as well, including particulate emissions, fossil energy depletion, ecotoxicity, and others.

What does this mean for a producer of systems for computer-aided design such as Dassault Systèmes? On the one hand, we can ask and expect that such a firm will continue to work on reducing its own footprint. But consider that the carbon footprint of Dassault Systèmes, France's largest software producer and one of the largest on earth, is on the order of 40,000 metric tons CO_2e. Application of this traditional focus on strictly reducing one's own footprint, limits our expectations and those of the firm itself to the pursuit of reductions on this order of magnitude. By contrast, setting our sights on the pursuit of NetPositive sustainability, by combining footprint reduction with handprint creation, sheds light on the fact that if Dassault Systèmes can pursue measures such as advanced training in eco-design and increased accessibility and power of eco-design functions within its design tools, it can enable sectors such as the global automotive sector to create handprints which are on the order of 10,000 times greater than its own footprint. Clearly, this is where its sustainability efforts should rightly be focused, for the good of humanity and the planet.

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[3] http://corporate.ford.com/microsites/sustainability-report-2013-14/doc/sr13.pdf

[4] Ecoinvent database: see http://ecoinvent.ch

[5] http://www.theguardian.com/sustainable-business/3d-printing-simulation-softwares-design-boeing-ford

[6] Based on vehicle simulations, Cheah et al (2010) assumed that fuel consumption reduces by 0.4 L/100km for cars, and 0.5 L/100km for light trucks for every 100 kg weight reduction. In other words, for every 10% weight reduction, fuel economy increases by 6% for cars, and 8% for light trucks. Cheah, L; Heywood, J.; Kirchain, R. (2010) The Energy Impact of U.S. Passenger Vehicle Fuel Economy Standards, presented at the IEEE International Symposium on Sustainable Systems and Technology, May 17-19, 2010, Washington, D.C.

[7] US Department of Energy "fueleconomy.gov" website: https://www.fueleconomy.gov/feg/download.shtml . We used the file "vehicles.csv" obtained via "datasets for all years (1984-2016)", updated 12 November 2015.

[8] Table 4.1, Transportation Energy Data Book, Oak Ridge National Laboratory. Available from ORNL http://cta.ornl.gov/data/chapter4.shtml

[9] Table 4.20 and 4.21, Transportation Energy Data Book, Oak Ridge National Laboratory. Available from ORNL http://cta.ornl.gov/data/chapter4.shtml

[10] About 18 percent of U.S. new-vehicle output, or 2.1 million cars and light trucks, was exported last year; Auto News, citing Wall Street Journal. Available from http://www.autonews.com/article/20150206/OEM01/150209875/u.s.-auto-exports-hit-record-in-2014

[11] http://www.statista.com/statistics/262747/worldwide-automobile-production-since-2000/