Towards Quantification of the Role of Materials Innovation in Overall Technological Development

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This article presents a method for quantitatively assessing the role of materials innovation in overall technological development. The method involves classifying the technical changes underlying the overall innovation process first within a set of functional categories and then within each category as a hierarchical array of technical changes. It is specifically found that about 2/3 of the total progress in computation over the past 40 years has been due to materials/process innovations. More speculatively, materials/process innovation contributes at least 20% of the progress in all areas and the relative contribution of materials/process innovation to overall technological progress has grown in the past few decades. © *2012 Wiley Periodicals, Inc. Complexity 18: 10–25, 2012*

Key Words: innovation; technological progress; hierarchy; functional progress; materials innovation

1. INTRODUCTION: WHY QUANTIFY AND WHY IS IT DIFFICULT TO DO?

Statements appear occasionally in the literature that materials innovation was associated with the earliest phases of technological development but that modern technology proceeds from a different basis than materials [1]. However, it can also be argued that materials innovations play a significant ongoing role in technological advance. The aim of this article is to present a reasonably objective method for quantifying the percentage of current technological development[1] that is attributable to

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[1] *It is quite likely that a much more nuanced statement would be necessary if quantification is pursued in some depth. Such a statement might recognize for example that materials innovation contributes different % in various technological areas (but it seems likely that in all instances it would be important (>10%) but just of variable importance and possibly differing amounts in different eras. The statement might also have to recognize that various definitions of materials innovation and differing methodologies for quantification would lead to ranges of quantification estimates.*

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materials innovation. Such quantification could provide useful input to R&D planning at various levels (global, national, firm, project, etc.). It could influence decisions regarding the research funding distribution among academic disciplines and perhaps the choice of majors among engineering and science students.

The desired quantification is challenging for a variety of reasons. Three important ones are described here. First, one notes that overall methodologies for quantifying overall technological progress are not agreed upon or fall readily to hand for such a task. Secondly, a basis for differentiation among types of innovation so that materials innovation can be consistently separated from other types of innovations is not known. Third, even if a consistent definition exists for different types of innovation, progress often occurs by development of a system or product that combines different types of innovation.

Given the severity of the challenges just outlined but also the potential high impact of results in the mode desired, this research was undertaken to explore the possibilities as well as to make some progress. The title of this article thus clearly labels progress toward as opposed to expected completion in this initial effort. This article addresses the three issues by theoretical consideration based upon literature review of prior research and through original research. Specific methods of addressing each of the three issues are given; they are, respectively: (1) a functional approach to technological progress, (2) a hierarchical description of contributing technical changes, and (3) comparison of progress rates in various levels of the hierarchy. Sections 2 and 3 address quantification methodology (the first problem), whereas Section 4 addresses separation and quantification of materials innovation (the second and third problems). Section 5 uses case studies to explore the suggested framework and Sections 6 and 7 examine implications and possible next steps.

2. QUANTIFICATION OF TECHNOLOGICAL PROGRESS

Five overall approaches to quantification of technological progress are outlined in this section and analyzed for possible utility in the task of interest, namely quantifying the role of materials innovation in overall technological progress. The five approaches are: patent analysis, Journal and magazine articles analysis, counts of major innovations combined with in-depth case studies, market share (or diffusion) of technological artifacts, and technical capability metrics dynamics. In the following subsections, each of these approaches is briefly described and analyzed for applicability.

2.1. Patent Analysis

There is a considerable body of research examining patents as a way to explore technological change [2]. A very appealing aspect of this approach is that extensive patent databases are available. Moreover, prior research [3, 4] has developed methods based upon citation analysis to attempt to identify key patents. Citation analysis and key word analysis might also yield acceptable methods for differentiating material innovation patents from other patent types. Thus, two specific research approaches could be: (1) to examine the number of patents per year overall and the number of those judged to be materials innovations and (2) to examine the number of key material innovations as a percentage of the total "key innovations"[2] over several years. The first of these is a bit easier (but the method for differentiating among innovation types by key words—necessary to get large numbers of patents analyzed—would involve a challenging research agenda. This approach has the drawback of essentially assuming that all patents are equally important to technological progress and this is of course also questionable. Although the second approach (key patents) may be a little more appealing to determine, a high-volume way to identify key patents would need to be developed and the applications thus far are quite limited.

2.2. Journal and Magazine Article Analysis

There has been some research using trade journal articles to follow innovations over time [5]. It would be difficult to translate this kind of work into an overall innovation or technological progress analysis and studies of many different types of Journals would be necessary to establish the relative contribution of materials innovation.

2.3. Major Innovation Counts

There has been a stream of research attempting to create lists over time of major innovations [6, 7]. If an analysis of such innovations were made in depth, one might get a sense of the contributions of materials innovations to major innovations over time. There are drawbacks to this approach and a major one is the lack of objectivity as to what is included in the innovation lists. A second significant shortfall is that the methods to be used in the in-depth study and the differentiation between material innovations and other types of innovation are unknown when combined in a single major innovation. In addition, even if these first two problems are solved a very high

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[2] *The ratio of "material" patents to total patents would be an estimate of the desired quantification in both cases described.*

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effort on a statistically significant number of cases would be needed to attempt quantification.

2.4. Market Share

Most research on technological change that has a quantitative character involves study of the penetration over time of a given technological approach, system, or artifact (we use the term TASA hereafter). Empirical studies starting with the penetration of hybrid corn as analyzed by Griliches [8] have proliferated [9, 10]. A variety of mathematical models have been developed [11] and shown to be in reasonable agreement with the empirical data so this approach is quite well established in describing an economically significant aspect of technological change. However, to estimate the importance of materials innovation in technological development using this approach would require study of the entire economy as well as characterization of the importance of materials innovation in all diffusion situations. The basic problem with this approach for our purposes is that market share does not focus on technological improvements but only on the overall substitution of one TASA by another.

2.5. Technical Capability Dynamics

The study of technical capability of TASA over time is another quantitative approach to technological change. The best-known prototype of this approach is Moore's Law which quantifies the number of chips per die in integrated circuits over time. This general approach is judged to have the best prospect of making progress in quantifying the role of materials innovation in overall technological progress and is thus described in some detail in Section 3. Of the four approaches covered in Subsections 2.1.–2.4., only patent analysis is judged worth pursuing further. However, here we have chosen to only further pursue technical capability dynamics because it is clearly superior to patents in describing the value of given incremental improvements in technology. However, a patent study such as outlined in Section 2.1. would certainly be worthwhile (and difficult) and essentially give an assessment (independent of that developed in this article) of the quantitative role of materials innovation in technological progress.

3. MEASURING TECHNICAL CAPABILITY

3.1. General Considerations and Figures of Merit

Technical capability for a TASA is generally the ability of that TASA to achieve its intended purpose. For measurability considerations, a narrower definition is used in this article that is consistent with this general definition. One aspect of the restricted definition is to consider measures of technical capability that are continuous and thus not simple yes/no measures such as considered by Lord Kelvin for powered flight.[3] Thus, a continuous measure of the ability (also called performance) to fulfill the purpose or function is of interest here.

A second narrowing for arriving at a definition of measurable technical capability is to not attempt to quantitatively assess the total utility of a TASA. Although there have been frameworks and approaches discussed for some time that attempt to describe the overall utility by one number or a hyper-surface [12–16] these have not been successful in even restricted cases in giving a truly measurable (as opposed to notional) indication of integrated technical capability. Thus, using such approaches to examine time dependence of a variety of technical capabilities to investigate the contribution of materials innovation to overall technological progress is desirable but is not (yet) feasible. Thus, our narrower definition: technical capability is a performance measure of a key intended technical function[4] of the TASA. This definition does not assure that the metric reflects well what is best from a user (particularly long-term) perspective but we will see that different metric types (described later) are not equivalent in this regard.

Numerous metrics for technical capability consistent with the definition just given have been proposed (and studied) for various technological systems. However, it is useful to define three subclasses of technical capability metrics: figures of merit, tradeoff metrics, and FPMs. The first of these has the broadest definition and are most numerous. We refer to them by the relatively widely used term in engineering—Figures of Merit—and show selected examples in Table1. Figure of merit is a technical parameter or set of parameters that relate to the functional performance of a TASA.

As this is the unrestricted class of metrics, there is a very wide array of possibilities and only a sample is represented by Table 1. Indeed, figures of merit such as these are known and used at least to some extent in almost all engineering work even though careful time histories are usually not available. Some consist of only one parameter while others are key ratios. The last example given is the only "efficiency" measure in the list but efficiency metrics are quite commonly monitored as engineering figures of

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[3] *He famously predicted that powered flight would remain impossible indefinitely shortly before the Wright brothers succeeded in achieving it.*

[4] *We use function here in a technical sense (a technically specific purpose) that is defined for a specific meaning below but the reader should note that the Technological Innovation Systems literature [17, 18] uses function in the sense of processes or subprocesses in technological innovation such as knowledge generation, entrepreneurial activity, etc.*

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TABLE 1

Selected Examples of "Figures of Merit" that have been used to Assess Progress in Technical Systems

TASA	Technical Capability Metric	Years Studied	References
Human Life expectancy	Population life span (national leader on global basis)	1845–2000	[19]
Apparatus for achieving low temperatures	Lowest temperature achieved (deviation from absolute zero)	1880–1950	[20]
Sailboats	Speed (1/time- between-ports)	1700–1855 1900–2105	[21, 22]
Gas turbines	Pressure ratio achieved	1943–1972	[23]
Aircraft engines	Horsepower	1927–1957	[24]
Farm tractors	Belt horsepower	1920–1970	[24]
Wireless telephone	Coverage- throughput per area	1900–2004	[25]
Tractor Engines	Horsepower-hour per gallon (efficiency)	1920–1970	[13]

merit. However, efficiency and most other figures of merit only poorly reflect the overall economic impact and do not reflect real engineering goals. Thus, our major focus in the further work is not on figures of merit but instead on two classes of metrics that involve a constraint in their formulation.

3.2. Engineering Tradeoffs

The second subclass of technical capability metrics is those that measure the performance of a TASA in achieving a key intended technical function relative to a resource constraint. These tradeoff metrics are less common in prior studies of technical capability than figures of merit but still have had reasonable representation as they are similar to productivity measurements. Examples of such metrics are given in Table2.[5]

These metrics have the advantage of directly relating to the desirability of the TASA as they maximize output (or meeting a key purpose or function) relative to a scarce input or resource (the usual resources are $, human effort and time but a variety of others are seen in Table 2). Improvements in and managing of such tradeoffs are at the heart of the engineering process (including invention and innovation). The levels of such tradeoffs over time are a superior measure of technical capability compared with figures of merit.

Koh and Magee [38] have recently described a generalization of tradeoff metrics by utilizing a generic approach to technical function that is described in Table3. The generic approach is based upon the idea that three basic operands ("things") are operated upon by five basic operations (processes) and that a generic function is defined by a basic process operating on one of the three operands [1, 39, 40].

Each intersection in the matrix (shown in bold type) in Table 3 is thus a generic technical function (typical devices and systems fulfilling these primary functions are shown as the entries). Although some prior technical capability tradeoff metrics are consistent with this functional approach, most are not because most prior metrics are defined for a specific technological approach. The metrics in Tables 1 and 2 are limited to the specific TASA shown with the exception of the watts/$ metric for solar photovoltaics which is generic as well as a tradeoff metric for this specific TASA. An advantage of the generic technical functional approach is that time series can be constructed for a variety of TASA that fulfill a given purpose but that are otherwise not related making possible the study of technical capability over longer time periods. A related disadvantage is that parametric details within a given TASA are not as well defined in the metric and thus linking progress to specific inventions is more difficult to achieve than for less broad metrics.[6] Our third subclass of technical capability metrics is thus Functional Performance Metrics (FPMs). These are defined as a measure of the performance (maximum for all TASA) in achieving a generic technical function relative to a resource constraint.

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[5] *In contrast to Table 1, this listing consists of a substantial fraction of those published but some others can be derived from electricity generation studies [26], from the desktop technologies studied in [27] and from [28].*

[6] *It is for these reasons that we will propose in Section 4.3 to simultaneously use FPMs and tradeoff metrics to explore quantification of materials innovations in overall progress.*

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TABLE 2

Selected Examples of Engineering tradeoff Metrics used for Assessing Progress in Technical Capability

TASA	Technical Capability Metric	Years Studied	References
Oil/gas discovery	Resources discovered per effort	1947–1998	[29]
Underground coal mining	Tons per man-hour	1900–1985	[30]
Commercial Aircraft	Speed times number of passengers	1925–1975	[20]
Bio processing	Titer for penicillin production (mg/L)	1945–1980	[31]
Jet turbines	Thrust per unit weight per fuel consumption	1943–1972	[23]
Genome sequencing	Base-pairs per $	1970–2003	[32]
Solar Photovoltaic Cells	Watts/$ (converted from price data)	1975–2004	[33, 34]
Computed tomography	Resolution details/mm/sec	1973–2005	[35]
MRI	Resolution details/mm/sec/$	1985–2000	[36]
Integrated circuits	Transistors per die	1960–2005	[37]
Wireless telephony	Spectral efficiency- throughput/Hz of channel bandwidth	1900–2004	[25]

FPMs that have been studied previously and the time periods are given in Table4.

3.3. Overview of Prior Technical Capability Results

Many of the metrics of all three types (at least when not reaching a limit) show an exponential (or greater see Kurzweil [42]) relationship between the metric and time. A very few existing cases will be reviewed here to have a feel for the kind of data being discussed.

Figure 1 shows an example of a functional performance metric—watts/l for the energy transformation generic function. This FPM shows reasonably consistent continuity over major TASA transitions and also shows exponential dependence with time. In this case, aircraft internal combustion engines and turbines show a fairly continuous exponential improvement. The overall FPM level of automotive internal combustion engines is not comparable with the aircraft engines showing the not surprising fact that cost and overall volume are not equally important for autos and aircraft. The graph also shows a different level (and perhaps slope) for electric motors which demonstrate that energy technologies have different FPM behavior for different energy forms as discussed by Koh and Magee [28]. However, in all energy forms and in all applications, the amount of power per unit volume shows a reasonably consistent trend over a fairly long time period.

Figure 2 shows a second example of a FPM-megabits/cubic centimeter for the generic function of information storage. It also demonstrates multiple TASA, an approxi-

TABLE 3

Generic Technical Functions Arrived at by an Operation (Shown in the First Column) and Operand (M, E, I) Resulting in a Matrix of Possible Technical Functions

Operation	Matter (M)	Energy (E)	Information (I)
Transform	Blast furnace	Engines, electric motors	Analytic engine, calculator
Transport	Truck	Electrical grid	Cables, radio, telephone, and Internet
Store	Warehouse	Batteries, flywheels, capacitors	Magnetic tape and disk, book
Exchange	eBay trading system	Energy markets	World wide web, Wikipedia
Control	Health care system	Atomic energy commission	Internet engineering task force

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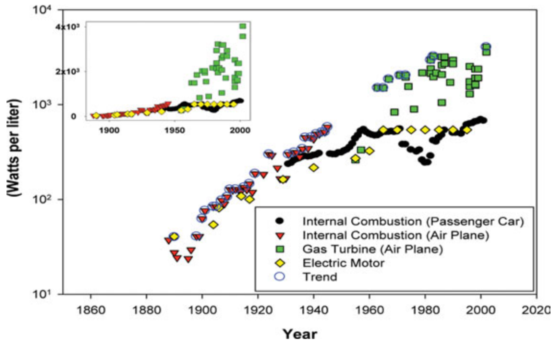
TABLE 4

Functional Performance Metrics that have been used in Assessing Progress in Technical Capability

Generic Technical Function	Functional Performance Metric	Years	References
Energy storage	Watt-hours per liter	1884–2005	[28]
	Watt-hours per kg	1884–2004	
	Watt-hrs per $	1950–2005	
Energy transport	Watts times km.	1889–2005	[28]
	Watts x km. per $	1889–2005	
Energy transformation	Watts per KG	1881–2002	[28]
	Watts per liter	1881–2002	
	Watts per $	1896–2002	
Information storage	Bits per cc	1880–2004	[38]
	Bits per $	1920–2004	
Information transport	Mbs	1850–2004	[38]
	Mbs per $	1850–2004	
Information transformation	MIPS	1890–2004	[41, 38]
	MIPS/$	1890–2004	

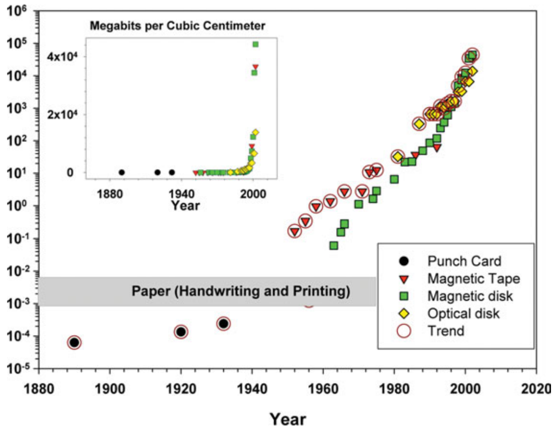
mately continuous exponential curve and a progress rate much greater than what is seen in Figure 1. The multiple TASA here include punch cards, magnetic tape, magnetic disks, optical disks, and paper which overall seem to also support the assertion of new TASA being involved in this relatively continuous (except for paper) exponential relationship of the metric with time. The much greater rate of progress for a functional FPM for a information technology (see Figure 2) than for a energy technology (see Figure 1) is consistent with the extensive results discussed in [28].

FIGURE 1



A FPM for information storage (megabits/cc) plotted logarithmically from 1890 to 2004–replotted from Ref. [38]. This shows improvement in information storage (per unit volume) over this period.

FIGURE 2



An FPM for energy transformation-specific power (watts/liter)–shown on a logarithmic plot from 1890 to 2002. This shows improvements in energy transformation over this period of time. Replotted from Koh and Magee [28].

As a last point in this section, it is worth noting that the exponential results found in all of these plots are consistent with a cumulative model for technological progress. The rate of advance is proportional to the current state as both depend upon applicable existing knowledge.

$$dFPM/dt = \alpha FPM$$
$$FPM_t = FPM_0 \exp(\alpha[t - t_0])$$

The second equation simply says that the performance metric at some time t, FPM_t is exponentially related to time with a rate of advance equal to α. A cumulative model is consistent with mechanisms such as partial transfer, hybridization and reciprocal restructuring such as discussed based upon innovation cases [43–45] and with simple combinatorial models such as by Arthur and Polak [46]. Thus, the exponential form is what is expected based upon detailed observation.

4. MATERIALS INNOVATION AND ITS RELATIONSHIP TO OVERALL INNOVATION

The preceding section introduced the foundation for the quantification approach that we propose to use in this work. The other challenges discussed in the introduction involve differentiating among types of innovations including materials innovations. Subsection 4.1 considers prior work in innovation theory that deals with types of innovations and the apparent differences relative to materials industries. In Subsection 4.2, we propose an exten-

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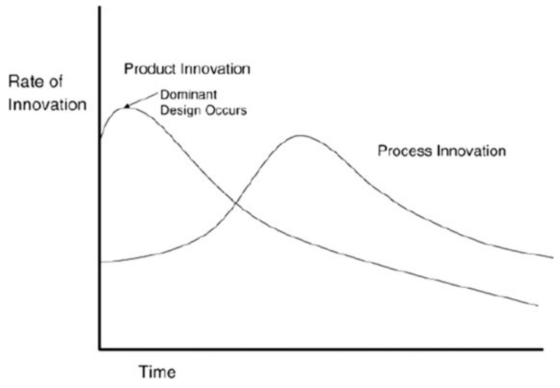
FIGURE 3



The Abernathy and Utterback [47] model of innovation life cycle in a product industry.

sion of this work that appears to be necessary for our task and in Subsection 4.3 we outline a framework for integrating Sections 2–4.

4.1. Models for Product and Process Innovation Over Time

Abernathy and Utterback [47] first differentiated innovation in assembled goods from innovation in homogeneous products, like chemicals and materials which are the output of process industries. They considered a number of examples of assembled goods and demonstrate that shortly after introduction of a product there are a large number of product innovations (see Figure 3). These product innovations are usually new product features but can also represent new product configurations. It has been suggested that a dominant design emerges which to some degree standardizes the product features and configuration in a way that satisfies large numbers of users. Once a dominant design emerges, product innovation decreases but process innovation increases as cost and efficiency become the competitive basis for the industry in question.

In their original work, Abernathy and Utterback suggested that the model shown in Figure 3 would not apply to industries where the output is a standardized item (materials for example). In later work, Utterback [48] suggested that for process and materials related products, a slight modification of the earlier model could be applied. He suggested that product innovation still occurs first but with a relatively lower intensity than with assembled products (see Figure 4). This early product innovation then falls off as process innovation rises. Utterback thus suggests that the difference in assembled products and nonassembled products is that nonassembled products have a lower intensity of product innovation and a higher intensity of process innovation. To support his model for innovation rates in materials industries, Utterback shows evidence from two cases. The two cases are plate glass and petroleum. In both cases, changes in the process were made deliberately to improve the product. Linton and Walsh [49] have recently pointed out that for innovation in materials industries, coupling of process and product changes are to be expected. They show evidence from four cases for this coupling. The four cases are:

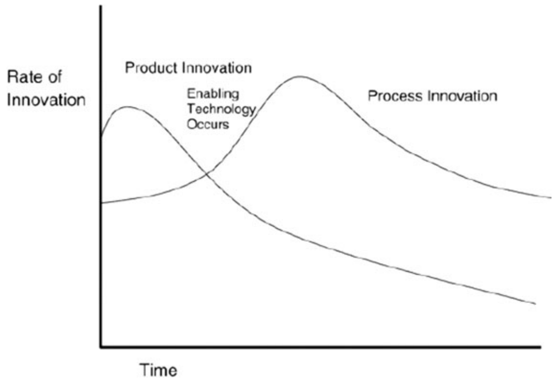
- Steel alloys from mini-mills (Chapparal Steel)
- Specialty chemicals (sulfuric acid and Barium Oxide from J. T. Baker)
- Food Products (Cadbury chocolate)
- Nanotechnology (ferrofluids from Ferrofluidics)

From all of the evidence, Linton and Walsh determine that Figure 5 best describes the time dependence of innovation in a materials industry.

4.2. Hierarchy of Levels of Innovation

The continuous coupling of materials innovations with process and product changes is an important input to our understanding of the role of materials innovations in overall technological progress. Throughout the rest of the paper, we will discuss coupled material process innovations as equivalent to “materials innovations”. However, the work reviewed in Subsection 4.1 focuses on the life cycles of industries and has little quantitative data on innovation rates but instead theoretical arguments about relative importance of process and product changes in certain types

FIGURE 4



The Utterback [48] model for innovation in a materials industry.

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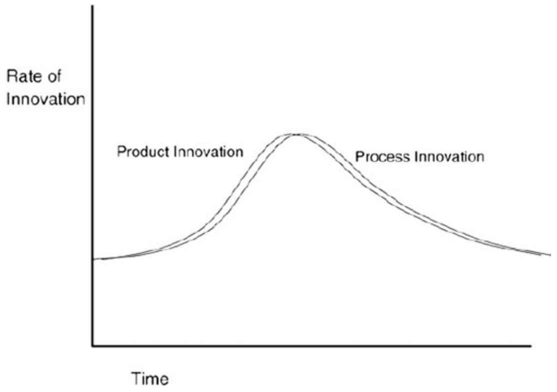
FIGURE 5



The Linton and Walsh model [49] for innovation in a materials industry.

of industries. Although the current author agrees that materials innovations couple process and product changes, there is no clear evidence or reason for the notional peak in Figure 5 and that increasing but coupled rates is more justified by the cases considered and the cumulative nature of technological change. Moreover, the separation of industry types while useful for management strategy considerations is not helpful in our case because innovations in materials industries are often sources for innovations in assembled goods industries. Indeed, the "product" of a process industry is usually a material that is used in components in assembled products. For example, improved steel products have been an important source of improved motor vehicles etc. Our attempt to quantitatively understand the role of materials innovation in overall technological progress requires that we explicitly consider these supply chain effects. A hierarchical framework for such effects is outlined here as a step in our quest to elucidate the role of materials innovation in overall technological progress.

At the highest level (which FPMs try to capture), technological progress is often achieved by introduction of a new TASA that achieves higher levels of performance than those it replaces. When viewed at large time scales (as for example in Figures 1 and 2), such discrete increases can appear as part of an almost continuous exponential. However, as the time increment is shrunken to years or months, it is clear that technological advance occurs in a discrete fashion (at amounts from a few percentage points improvement to factors as large as 100% improvement). A given new TASA actually incorporates improvements of various kinds and each of these improvements can be conceived as belonging to a hierarchy of technological innovation types. A generic hierarchy to describe elements of the changes that occur is suggested here.[7] The elements of the hierarchy (the ranks are listed in "ascending" order) for improving an overall technical system are:

- Incremental improvement in material/processes (and algorithms) that make up devices and components in the technical system can improve the overall system performance (hereafter shortened to Materials/Processes Improvement)
- Discrete change in the choice of materials/processes (and algorithms) used in the components and devices that make up the system can improve the system (hereafter referred to as Materials/Process Substitution)
- Changes in(nonmaterial or process) parameters that are internal to various devices and components can be made to improve the overall system(hereafter referred to as Component Redesign)
- Changes in relationships among different components and devices that make up the system can be a source of improvement in the overall system (hereafter referred to as System Redesign)
- The basic scientific phenomenon being used in the system or in devices that are part of the system can be changed to improve the overall system (hereafter referred to as System Phenomenon Change)
- The operating procedures for the overall system can be changed to improve the overall system (System Operation)

This generic listing makes it clear that materials and processes are always at the lowest levels of such hierarchies and are therefore easy to "miss" in describing technological change in a broad way. We thus expect to find such changes in any serious look at technological progress. However, we also see that not all technological progress (as radicals of that view of progress might assert) will be attributable to materials innovation. We now integrate the ideas of Sections 2 and 3 with those in Section 4 to arrive at our method for arriving at quantitative estimates of the role of materials innovation in overall technological progress. This framework is what will be explored further in the case studies in Section 5.

4.3. Framework for Quantification of Materials Innovation

The framework for our method results from combining the concept of different types of metrics for measuring technical capability progress with the concept that the technical changes that underlie technical progress over time can be described by the hierarchical levels described

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[7] *A hierarchical description of technological trends has been suggested by Van Wyk [50] but with a different purpose and structure.*

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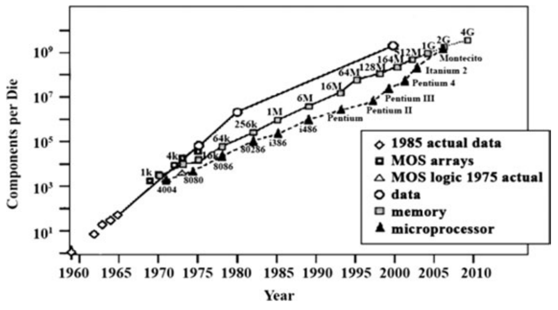
in Section 4.2. As the process/material couple occurs at the lowest levels of the technical change hierarchy, finding lower level metrics that characterize the material/process contribution is the key step in arriving at a quantitative estimate of the role of materials innovation in overall technological progress. Progress rates in such metrics can be compared to higher level FPMs that describe overall progress in a generic functional category.

We thus propose assessing overall technological progress in different generic functional areas as described in Table 3. The two papers of Koh and Magee [28, 38] give long-term results for six of these generic categories and our further work will be based upon these six functional categories (information storage, information transport, and information transformation as well as energy storage, energy transport, and energy transformation). In our first case, information transformation, a sufficiently detailed metric (Moore's law) at lower levels exists to make an estimate of the contribution of materials/process innovation to the functional technological progress. In addition, much analysis of this technology has been made and thus independent examination of the results is undertaken. In the other five cases, we describe selected technical changes (innovations) in each generic functional area using the hierarchy described in Section 4.2. This will serve to demonstrate the generic hierarchy in a variety of very different cases and allows identification of possible lower level metrics that might be invented and examined to accomplish other quantification cases in the future.

5. QUANTIFICATION CASE STUDIES

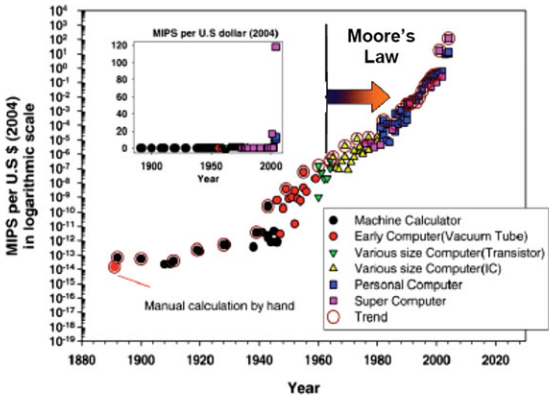
In this section, we first consider the generic functional category of information transformation particularly relative to Moore's Law, integrated circuits, and computational improvement. We then broadly look at the other five generic categories by developing examples of important innovations in each functional category in the format developed in Section 4.2—a technical change hierarchy.

FIGURE 6



Moore's Law for integrated circuits, a logarithmic plot of Components per die from 1960 to 2010. Data and figure from Moore, [37]; MOS is metal oxide semiconductor.

FIGURE 7



An FPM for information transformation, millions of computations per second per dollar versus time (from 1895 to 2004) plotted logarithmically. The regime where Moore's Law applies is for Integrated circuit computers and is also shown. Data are from Refs. [38, 41, 51].

5.1. Information Transformation (Computation)

Figure 6 depicts transistors per die according to Moore's law. We note the exponential relationship and the fact that this tradeoff metric increased by seven orders of magnitude in the 40 years after Moore made his prediction and is still in rough alignment with his forecasts. It has been generally recognized that Moore's Law is an essential underlying factor in the ongoing increases of computations per second per $ for computers based upon integrated circuits. This broader generic functional metric (for information transformation) is one of the FPMs listed in Table 3 and it is plotted in Figure 7 against time starting early in the 20th century. This relationship is also exponential and as first noted by Moravec [41] and Kurzweil [51], the FPM yields a continuous curve that includes results from computers that predate integrated circuits (nonintegrated transistors, vacuum tubes and mechanical systems).[8] Thus, the ability to study technological progress

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[8] *As noted by Nordhaus [52], the rate of improvement is much faster beyond ∼1940 than before and this coincides with transition from mechanical to electronic systems. A similar change in slope for information storage also accompanied transition from mechanical to electronic technologies—see Figure 2.*

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over numerous TASAs in a given functional area is apparent and continuous exponentials despite different TASAs is seen in this example. A clear differentiation between major improvement to an existing TASA and a new TASA is one of those aspects of technological change that are difficult to define operationally. However, the overall transition from a mechanical analogue computer (not to mention hand computation) to an integrated circuit digital computer clearly stands as a case of new TASA within the generic functional category of information transformation. Thus, we have for this generic functional area both an overall functional as well as a lower level quantitative metric.

Comparison of the two metrics leads to an important conclusion. The underlying tradeoff metric does not progress as rapidly as the FPM. Even within the Moore's Law era, the generic function increases by $\sim\times30$ more than the transistor tradeoff metric as Moore made his prediction (10^9 vs. 3×10^7 increase for the FPM vs. the tradeoff metric from 1965 to 2004). This is not surprising as there are many other technical factors affecting computation that are changing as well as the number of transistors per die during this period.[9] The additional technical changes apparently contribute (net) about 8% a year to the overall generic functional metric progress rate (~5 doublings in 40 years). We can use this fact to arrive at our first quantitative estimates of the role of materials innovation in overall technological progress. If we simply assume that all of the Moore's law effects are due to coupled materials/process innovations and that none of the other effects are due to materials, we obtain an upper bound estimate that ~84% of the annual progress (~42%/50% annual progress in Figure 7 during the period in question) in computation is due to coupled materials/process innovations. This estimate is treated as an upper bound because none of the changes that improve computation performance in this period and do not affect Moore's law are likely to be materials and process related.

The next step in arriving at our best estimate from this upper bound is to consider in more depth what is known about semiconductor progress and the semiconductor industry. We do this in order to assess how much of that progress should be ascribed to materials and process innovations. Because of its importance and due to widespread knowledge of the rapid advance defined by Moore's Law, there has been substantial work in this area. The evolution of companies, competition, and specific technological developments has been well studied. Important summaries and syntheses of much of this work are in Walsh et al. [53], Moore [37], and Brock [45].

One issue of interest is to examine the core competencies that have been found to operate in different epochs during the 40+ years of semiconductor integrated circuit technology. Walsh et al. [53] treat this problem in some depth and consider seven epochs from 1947 to 2000+. They define (in three pages of appendices) a list of 23 separate "relevant competencies/capabilities." Major categories that they use to group these 23 competencies include Silane chemistries, inorganic chemistry, crystalline materials, environmental processing, and wafering, which obviously broadly support the idea of materials and process-based innovations being very important in the various epochs. Reviewing the detailed descriptions of the core competencies in, Walsh et al. establishes that materials/process coupled competencies were the dominant competencies throughout the entire period with one clear exception—they identify "semiconductor device design" as a critical core competency in the first epoch (1947–1960). Therefore, the next step in our quantification of the contribution of materials/process innovations to overall computation progress is to estimate the contribution of "semiconductor device design" to Moore's Law.

If we simply follow Walsh et al. dating and disregard lag effects, we might conclude that semiconductor device design (whose importance as a competency Walsh et al. end in 1960) contributed little to Moore's Law (which was first declared in 1965 by looking back to 1960). However, this is not accurate as some of the increase in components/die in the early years was due to component design effects. Moore [37] reviews this in some depth and gives Figure 8 as the breakdown he saw when he made his second projection in 1975. Moore makes the point that the larger slope in his earliest prediction (the solid line up to 1980 in Figure 6) was due to component design effects which saturated by the early 1970s (Moore first thought they might proceed until 1980 but said in 2006 that his earlier assumption was incorrect). Indeed, the slope change for the measured data in Figure 6 occurs at about 1972.

If we use Figure 8 to assess the contribution of device design (called device and circuit cleverness in the figure) up to 1972, one estimates that a factor of ×30 improvement came from this source. Over the full 40 years of Moore's Law, this factor of 30 amounts to another ~8% per year improvement not due to materials and process. Thus, our combined estimate of the progress in computation due to materials and process innovation is slightly more than 2/3 (34%/50%) of the total progress. This second estimate is considered moderately firm because other contributions to Moore's Law that are not materials/process related are likely to be quite small (and possibly offset by small materials effects in the nonMoore's Law part of the improvement in computation).

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[9] *Although FPMs are not a total utility metric, the use of key outputs and critical resources in generic functional areas does come closer than narrower metrics to capturing overall technological progress.*

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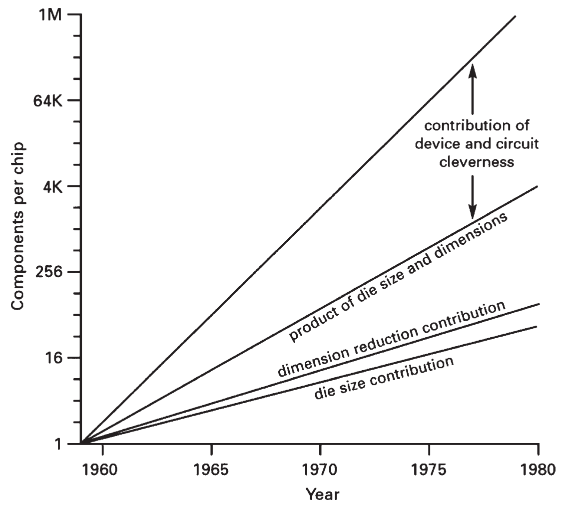
FIGURE 8

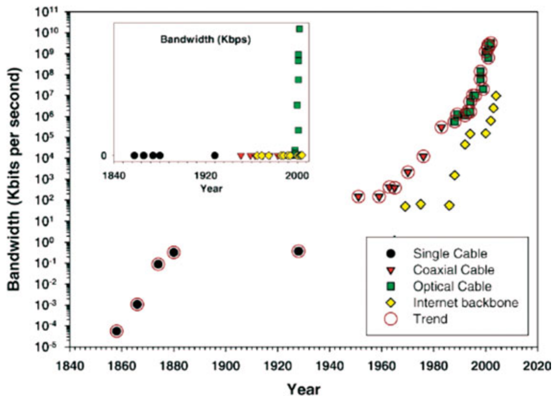


From Moore [37]; Contributing factors to components per die in the early stages of Integrated circuit development.

5.2. Information Transportation

Figure 9 shows the outstanding progress made in information transport over the past 150 years. The technical capability metric in this case increases about as rapidly as the one for information transformation but is not as widely known.

FIGURE 9



The change in bandwidth for the undersea cable system over the past 150 years–from Koh and Magee, [28].

TABLE 5

Examples of Technical Changes in the Information Transport Functional Category Arrayed in the Technical Change Hierarchy Developed in Subsection 4.2

Category of Change	Examples
Materials/Process Improvement	Coatings on glass fibers; purity of glass
Materials/Process Substitution	Glass fibers vs metallic conductors
Component Redesign	optical “solitons”
System Redesign	optical amplification
System Phenomenon Change	Wireless vs wired transmission
System Operation	TCP/IP; wavelength division multiplexing

Clear exponential behavior with a 70 year hiatus (voice transmission was not feasible until coaxial cable was available) is seen in the chart. Some of the evolving technological innovations are broadly indicated but these are not sufficient to determine the role of materials innovation in this functional area. To help in this regard and to make the hierarchical approach more concrete, a hierarchy of technical changes in this area was developed. Table5 gives examples for each hierarchical category described in Subsection 4.2 of technical innovations that contributed to technological progress over the past 35 years (a period when the FPM of bandwidth increased by ~7 orders of magnitude—see Figure 9).

It is clear that materials innovation contributed to progress in this functional area. The development and tremendous improvement in glass fibers have made substantial contributions to overall technological progress to information transportation. However, we have not found a progress metric or its time dependence that allows us to assess how much of the overall progress was due to glass fiber developments or other coupled materials/process innovations. Tradeoff metrics (1) describing glass fiber transmission loss (dB/km) and (2) low loss bandwidth in fibers over time would make a good start in allowing a reasonable estimate of the contribution of materials/process innovations to overall progress in this functional category. Based upon limited data, it appears that material/process improvements to optical fibers have contributed about 40% of the overall progress (five orders of magnitude in Figure 9) that has occurred since the introduction of optical fiber systems. This estimate is not considered reliable because of the lack of publication of appropriate lower level metrics in this functional area.

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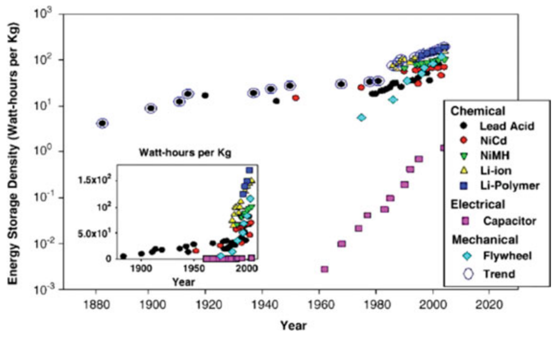
FIGURE 10



Energy stored per kilogram from 1880 to the present from Ref. [28].]

5.3. Energy Storage

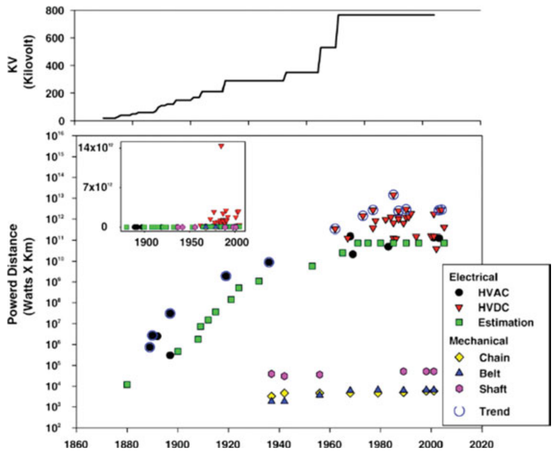
Figure 10 shows the progress made in energy storage over the past 125 years. In this case, the rate of improvement is much less than the rates for the two information technology examples that preceded it but the FPM still increased by ~100 over the time period. Because of this relatively slow rate of progress, the exponential nature of the relationship is often not noted. However, the long time period allows one to ascertain that an exponential relationship is superior to a linear description (see inset linear figure). The figure shows that various battery technologies have superseded one another in this metric. The figure also shows that capacitors (and flywheels) are progressing much faster than batteries but neither has yet reached the energy storage density of current batteries. Table6 shows an example set of known technical changes in energy storage that have contributed to overall technological progress in this area. The table again uses the technical change hierarchy developed in Subsection 4.2 as the framework.

TABLE 6

Examples of Technical Changes in the Energy Storage Functional Category Arrayed in the Technical Change Hierarchy Developed in Subsection 4.2

Category of Change	Examples
Materials/Process Improvement	Lead casting techniques
Materials/Process Substitution	Lead to Ni-Cad to Li-ion
Component Redesign	Honeycomb structures for anodes
System Redesign	Parallel cells
System Phenomenon Change	Batteries to capacitors
System Operation	Charge sensing

FIGURE 11



Improvement in feasible power × distance (powered distance) over time for energy transportation–from Ref. [28].

There are clearly significant contributions of coupled material/process innovations to overall technological process in energy storage. All modes studied (batteries, flywheels and batteries) show clear contributions from materials/process innovations. Indeed, as batteries are still the leading energy storage device, one is tempted to conclude that a large fraction (perhaps 80% seems believable) of the improvements seen in Figure 10 are due to materials innovations. However, this conclusion must be regarded as less reliable than the estimate made for information transformation (computation) because detailed attempts to characterize the nonmaterials changes have not been made.

5.4. Energy Transportation

Figure 11 shows the substantial progress in energy transport made over the past 150 years. The metric in this case captures the increasing distance and power that became feasible over time. The relationship is again exponential and all of the ~10 orders of magnitude of progress shown in Figure 11 occurred when electrical transport of energy was the leading technical approach. Prior progress at a slower rate seems certain to have occurred when mechanical transport of energy by chains, belts, and pulleys was dominant before ~1880. Although much of the progress occurred by higher AC voltages (shown at the top of the figure), the leading power transmission technique now is high voltage DC (a new TASA in this generic functional

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TABLE 7

Examples of Technical Changes in the Energy Transport Functional Category Arrayed in the Technical Change Hierarchy Developed in Subsection 4.2

Category of Change	Examples
Materials/Process Improvement	Al purity
Materials/Process Substitution	Insulators to allow higher AC voltage
Component Redesign	Ball bearings
System Redesign	Transformers and voltage step-down
System Phenomenon Change	Mechanical to electrical transmission
System Operation	AC vs DC power

area). As in all cases, a wide variety of technical innovations are responsible for the improvement in the generic functional area. Examples are shown in Table7 organized again by the technical change hierarchy developed in Subsection 4.2.

Coupled materials/process innovations have made a contribution to improvement in this generic functional area with improvements in dielectric breakdown for insulators as one example. However, no sub level metrics of relevance have been found. Thus, no quantitative estimate of the role of materials innovations in overall technological progress can be made for this case.

5.5. Information Storage

Figure 2 showed the outstanding progress made in the past 90 years in information storage. We again see clearly exponential progress and in this case 6 orders of magnitude improvement over the past 50 years. The progress is particularly rapid once the dominant technologies became electronic as opposed to mechanical. As in all cases, a wide variety of technical innovations are responsible for the improvement in the information storage generic functional area. Examples are shown in Table8 organized again by the technical change hierarchy developed in Subsection 4.2.

It is again clear that coupled materials/process innovations have made substantial contributions to the overall progress in this generic functional category. It appears to be a category that a very high contribution of materials has been (and is being) made. In the case of information storage by semiconductors, Moore’s Law applies with its domination by materials/process innovations. Substantial materials contributions seem clear for magnetic, optical magneto-optical storage devices but no subsidiary technical metrics have been found to allow one to make a quantitative estimate.

TABLE 8

Examples of Technical Changes in the Information Storage Functional Category Arrayed in the Technical Change Hierarchy Developed in Subsection 4.2

Category of Change	Examples
Materials/Process Improvement	Improvements in integrated circuit technology
Materials/Process Substitution	New optical and magnetic materials and processes
Component Redesign	Magnetic disks vs. magnetic tape
System Redesign	Magneto/optical storage
System Phenomenon Change	Mechanical to electronic and magnetic-optical
System Operation	Database architecture

5.6. Energy Transformation

Figure 1 showed the progress in energy transformation over the past 110 years. The relationship with time is again exponential and a wide variety of innovations contributed to the progress. Table9 shows examples and there are clear materials/process contributions to overall technological process. However, once again no lower level metrics were found.

TABLE 9

Examples of Technical Changes in the Energy Transformation Functional Category Arrayed in the Technical Change Hierarchy Developed in Subsection 4.2

Category of Change	Examples
Materials/Process Improvement	Improvements in high temperature alloys –Ni based, etc
Materials/Process Substitution	Ni for Fe, ceramics for metals
Component Redesign	Fuel injectors
System Redesign	Feedback control for combustion
System Phenomenon Change	Electric motors vs. combustion engines
System Operation	Control strategies for engines and motors

6. DISCUSSION OF RESULTS

In this section, we examine what the results in Section 5 tell us about the quantitative role of materials innovation in overall technological progress. There are two key aspects to investigate relative to the indications of quantification of coupled materials/process innovation in total technological progress offered from the cases reviewed in Section 5. One question is how large a contribution has been made and a second is how that contribution has been changing over time. The first of these topics is addressed in Section 6.1 and the second in Section 6.2. In Section 6.3, the method that we have used is assessed in light of the findings thus far. Section 6.4 looks at what these preliminary results might indicate about overall technological progress and the role of coupled materials/process innovations.

6.1. Summary of Quantification Results

In the six functional categories studied, we arrived at one reasonably firm estimate of the quantitative role of coupled material/process innovations to overall technological progress. The estimate for information transformation (computation) over the past 40 years is that about 2/3 of the overall progress is due to materials/process innovations. Although this might seem high to those who have not looked in depth at progress in information transformation, it appears reasonable in light of what is known about that industry over the past 40 years. We were unable to arrive at a firm estimate for the materials role in any the other five generic functional categories. However, the technical change hierarchies developed in these cases indicates to this author that in none of the cases is the material contribution likely to be less than 20%. In the case of energy storage, the contribution of coupled materials/process innovation is quite likely to be an even larger ratio of overall technological progress than that found in information storage (>2/3).

6.2. Trends Over Time in the Importance of Coupled Material/Process Innovations to Overall Technological Progress

As Subsection 6.1 summarizes, the impact of coupled materials/process innovations on overall technological progress is quite high. As one potential value of quantification is as an input to R&D planning, some attempt to forecast such impacts would be useful. As an indication of the future impact, a very important issue is whether the quantitative importance of material/process innovations have been increasing or decreasing with time. Indeed, there has been a suggestion that the importance of materials technology has been diminishing for some time because it supposedly preceded energy technology which has now given way to information technology [1].

Section 5 gives no direct evidence on time dependence of the impact of material/process innovations as we would need estimates of the importance at a number of times for several generic functional categories and we have only one firm estimate for one period. Nonetheless, one can rationally speculate in a few cases. In all three information functional categories (information transformation, information transport and information storage), the contribution of material/process innovations is harder to find in the era when mechanical rather than electronic forms of technology were dominant in these functions (generally prior to 1945 in all three cases). Thus, in these functional categories the contributions of materials innovations has increased over the last century. In all three energy categories, ongoing contributions of materials innovations suggest that approximately constant ratios are probable. Although our evidence is at best sketchy, it does seem to indicate increasing quantitative importance with time for coupled material/process innovations in overall technological progress.

6.3. Implications to Methodology

The most important result from the current work is that we were able to make one reasonably solid quantitative estimate of the importance of materials/process innovations to overall technological progress. Thus, the framework developed here and discussed in Section 4.3 is viable. The framework involves using metrics from several levels (generic functional at the top level and specific relevant tradeoff metrics or figures of merit at lower levels) while simultaneously developing technical change hierarchies to guide one in the selection and use of the lower level metrics.

The major limitation of the current method is also potentially visible at this early stage. The existence of well formulated and documented tradeoff metrics that characterize progress at the level of materials/process innovations is apparently limited at the present time. In the case of the well formulated and documented Moore's Law, data exist for more than 40 years and evidence of causes at even lower levels exist. Ideally, we would like to have such metrics for all six generic functional categories and for even longer time periods than exist for information transformation (essentially only the Moore's Law period has the required documentation).

6.4. Broader Consideration of Technological Progress

The generic functional category approach was conceived as a generic way to describe all of technology. Although it does so reasonably well, there are clear limitations to the status to what we would have even with solid estimates in all six generic functional categories discussed in Section 5. First, there are at least nine functional categories suggested in Table 3 that have not yet been studied. Moreover,

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study of a few metrics in each category (as approached here) does not begin to study all aspects of technological progress. Examination of the published tradeoff metrics (Table 2 in Section 3.2) gives one a glimpse of the breadth of technological progress factors that are important in overall technological progress. Each of these progress trends can have potentially different importance for coupled material/process innovations. The indication from Sections 5 and 6.1 is that our six categories show significant variation in the importance of materials and thus no general single number seems appropriate to state at this time. It does appear to this author that if one includes biological materials in the coupled material/process innovation category, there are not likely to be any progress trends where materials do not account for at least 20% of the overall progress.

In additions to the speculation about time dependence in Section 6.2, one can add a comment from this broader perspective of overall technological progress. In this regard, I note that in general technologies that improve as scale reduces—as discussed first by Feynman [54]—are those that are currently improving most rapidly. These technologies are therefore growing in their contribution to overall technological progress. Such technologies (micro and nano technologies) are almost by definition dominated by materials/process considerations. Thus, from a general perspective one expects the importance of materials innovation to be increasing at the current time.

7. CONCLUDING REMARKS

The preliminary study on quantification of the role of materials innovation has several key findings:

- The coupled approach using multi-level metrics with multi-level assessment of technological change can lead to reasonably firm estimates of the importance of materials innovation. For example, for information transformation (computation), the methodology indicates that materials account for $\sim 2/3$ of the total technological progress (over the past 50 years) in this generic functional area.
- More speculative assertions based upon the partial results are that the importance of coupled material/process innovations is increasing as a ratio of total technological progress over time and can be expected to more important in the future. Moreover, there appear to be no functional categories where the contribution of materials innovation is less than 20% of overall technological progress.
- More attention to metric dynamics in case studies of materials innovation would increase the number of cases where the role of coupled materials/process innovations is able to be quantitatively estimated.

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