Tool theory and the urban data medium: Data driven visual tools for urban energy

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***Abstract*—What is the nature of data driven tools for digitally augmented urban environments? This paper addresses issues related to tool theory for the new breed of tools based on data streams generated by digital systems in urban environments. To get a better understanding of the nature of these tools I propose a viewpoint that brings together three established tool theories that approach the topic from different angles. I argue that the data driven tools in discussion cannot be adequately discussed by any one of these theories but require a combination of the three different theories. An example from my recent practice, based on urban energy systems data, serves to illustrate the conceptual framing of data driven tools at the intersection of the discussed theories. By bringing together the views on tools as 'extension of man', 'virtualization of action', and as 'memory of social activity' I invite designers and developers to investigate the nature of data driven tools afforded by the increasing pervasiveness of networked digital technologies in urban environments.**

Keywords*— *systems data; urban environments; tool theory; energy systems; data visualization

I. Introduction

The pervasiveness of networked digital technologies in urban environments has given rise to a wide array of novel urban services. In addition, the massive amounts of data resulting from these networked operations have given rise to a radically new way of understanding urban dynamics and designing for urban environments [1; 2]. Data generated by urban digital systems is a compelling 'material' to work with because of a number of reasons, which include that it is: (1) generated without further sensor deployment and thus can be relatively inexpensive, (2) accessible in real-time, (3) accessible over spatial and temporal distance, (4) often incidental to and tightly linked to human activity in urban space (5) generated in machine readable formats that allow for further processing and combination of data from diverse sources.

This paper focuses on dynamic visual tools for data specifically generated by urban energy systems. In order to grasp the significance of the availability of this kind of data for the development of new urban data tools, it is worthwhile to recall the pre-digital and pre-networked scenario of data collection in this domain.

Electric metering first became an issue when it was used for powering spark lamps in the 1870's and the need arose to bill customers. Since each lamp's required voltage was known and the current was constant, the unit of measurement that emerged was lamp-hours and related simply to the measured time of current flowing through lamps. As electricity powered devices became more diverse, a number of devices for measuring were invented using different approaches: chemical ampere-hour meters based on zinc plates connected to the customer's circuit - electrodes were then weighed each month to establish billing; induction meters as AC became available; etc. What was common to all of these approaches was that the act of reading values was a manual and in-situ process and in early cases required the substitution of material for measuring purposes [3]. Automatic readers did not emerge until the 1970's with Paraskevakos' patent for a remote meter based on the automatic telephone line identification system [4]. Automatic meter reading has since moved from monthly readings to instant always-on systems providing remote readings at hourly or smaller intervals. 'Smart meters' are a further development in that they enable two-way communication between the utility provider and the client metering device.

Metering of energy consumption has shifted from an 'after the fact' reading for billing purposes, to a real-time information exchange to dynamically support effective supply and consumption behavior [5; 6]. As such, an energy flow is a flow of information and represents a much larger potential for new use scenarios due to the tight spatio-temporal connection between data and activity.

While traditional metering tools were effective for billing purposes, what then are the challenges in transforming present day data streams into tools capable to foster understanding and support action? How can we move from a vision of data for accounting purposes to one of data that informs understanding and becomes part of the activity as a new kind of *tool*? This paper proposes a viewpoint based on three key tool theories. A case study that focuses on data driven visualization tools for urban energy systems is also presented.

II. Tools as a Viewpoint

There is no doubt about the dramatic increase in data generated by pervasive digital technologies on a continuous basis. Eric Schmidt's quote from 2010 about how we create every two days as much information as we did from the dawn of civilization up until 2003 [7] has been often cited and points to a trend that is only bound to grow as the number of digitally connected objects grows [8]. Whether these amounts of data are considered too large, does not depend on the amount itself, data is not inherently big or small. Rather, it depends on the tools available to deal with any amount and kind of data, and whether these tools are adequate for the work envisioned [9].

Shifting the focus on tools then, considerable effort has gone into the development of increasingly capable technical frameworks to deal with data storage, messaging, processing, etc. This effort focuses on machine-data interaction to enhance efficiency. The other facet of this challenge lies in the human-machine or human-data interface. How to conceive appropriate cognitive tools for human users to access the wealth of information concealed in data? Focusing on the tool aspect of the issue at hand there is sound conceptual understanding in existing theories that can guide the process of designing new tools for the 'data deluge' by reflecting on the very nature of tools as such.

A. *Technology as extension of man*

In his seminal work from 1964 [10], Marshall McLuhan describes a prosthetic view on technology. The basic characteristic of technical objects is that of extending the human organism by replicating or amplifying bodily and mental abilities. Technologies are for McLuhan extensions of man's physical systems when they increase power and speed and of man's cognitive system in as much as they augment functions of the senses, the central nervous system and more in general of consciousness. Considering some basic mechanical tools such as knives, bows and spears, they can be analyzed as extensions of hands, nails and teeth. Clothing protects from the elements and can be viewed as an extension of the human skin and hair to extend its intrinsic capacity for heat control and physical protection. Mechanisms are analyzed at a high level view as assemblies of parts that relate to specific body postures or movements. Mechanization of a task is viewed as a subdivision of an activity into smaller steps translated into repeatable actions executed by moveable parts. Media, McLuhan's central focus, is analyzed as an extension of the senses such as sight and hearing. As such, radio and telephone function as extensions of the ears, and visual media augment man's visual systems. Electronic media are analyzed as extensions of humans' capacity for processing information. As such, these technologies augment on the central nervous system's capacity to store, manage, and retrieve information. "By putting our physical bodies inside our extended nervous systems […] – all such extensions of our bodies, including cities – will be translated into information systems. Electro-magnetic technology requires […] an organism that now wears its brain outside its skull and its nerves outside its hide" [10].

B. *Tools as virtualization of actions*

More than an extension of man alone, Pierre Levy views the dynamic of technology as driven also by its own products [11]. Transversal and rhizomatic combinations that generate functionalities often very distant from man's capabilities – consider entities such as a sailing boat or a nuclear power plant. They can neither be considered extensions of a single body, nor extensions of man. The invention of a tool, a machine, virtualizes a combination of people, actions, and pre-existing tools. Invention of a new tool is the partial materialization of a generic function, not of a particular need. It creates a point of reference for a category of problems. More than the extension of man, a tool is, for Levy, the *virtualization of action*.

What is the 'virtual' that Levy means in his discourse? Derived from the Latin "virtualis" or "virtus", meaning force, potence, by a scholastic definition the *virtual* exists in its *potential*, not in its *act*, not *actually*. The tree is *virtually* present in the seed. All the information necessary to grow the tree is already present in the seed, but the tree is not a simple realization of this information. Its growth is impacted by numerous factors in its environment (water, sun, etc.). The *virtual* is a problematic complex, an intersection of tendencies and forces that accompany a situation, an event, an object or any other sort of entity. It requires a process of transformation to become *actual*: a process of *actualization*. Actualization is like the solution to a problem. The *virtual* contains all information necessary to *actualize*, it contains the whole set of problems, all constraints. The *virtual* is not the opposite of the *real*, but of the *actual*. Virtual and actual are only two different ways of being. The real, instead, is the opposite of the possible. The possible is fully formulated but not yet realized. It will realize without changing anything in its determination and nature [12].

Tools, in Levy's framework, emerge by taking a physical or mental function of man (catching, beating, calculating, etc.) and then separating it from a specific assembly of bones, muscles and neurons, and from a specific interior and subjective experience. The abstract function obtained in this way can then be materialized in forms very different from habitual gestures and movements. The resulting hybrid devices can substitute the natural body (fishing rod, mathematical formula, etc). If the hammer might seem like an extension of the arm, the wheel certainly does not give the idea of an extension of the legs, it is a virtualization of walking. A hammer virtualizes the concrete action of beating, it creates a potential. The absence of a hammer is a limit, while the presence of a hammer is an open eventuality. There are few virtualizations of actions and many actualizations of tools. The hammer could have been invented three our four times at different moments in history (virtualization) but there have been billions of beatings done with hammers (actualization) [11].

C. *Tools as mediators and memory of social activity*

A third theoretical framework, which is of significant importance to the role of tools, is Activity Theory. Activity Theory is a social theory of human consciousness based historically on work done by Aleksei N. Leontiev [13] in 1970's and later by Lev Vygotsky. It became more popular in the 1990s especially in the context of designing human-machine interactions [14; 15]. Activity Theory seeks to understand the unity between consciousness and activity with consciousness viewed as the product of an individual's interaction with people and artifacts in the context of *everyday practical activity*. Consciousness is realized by what we *do* and Activity Theory poses a primacy on the *activity* over the *subject* and the *object* as prime unit of study. Through the study of an activity both subject and object can be understood as activity forms them. In this viewpoint, tools are considered mediators between subject and object. They mediate between people and the world. Tools shape the way human beings interact with their environment and their reality and by shaping external activities they eventually shape internal ones. Tools reflect the experience of other people with an activity. These people formed the tools based on their attempts to solve a problem, the experience is accumulated in the structure of the tool. In this way, the creation and the use of tools is an accumulation and transmission of social knowledge over time and tools can be viewed as *memory of an activity* [16].

D. *A viewpoint at the intersection of three tool theories*

These three frameworks were developed before the advent of the level of pervasiveness of urban digital technology systems discussed here. Yet, each of them by themselves continues to play an important role in related research: McLuhan's framework of technology as extension of man has been referred to in the context of networked public displays [17], or in regards to pervasive urban information technology networks [18]. Levy's concept of virtualization and technology continues to play a key role in understanding current discourses and dynamics in digital media [19; 20]. Activity Theory has been developed extensively since the 1990's in the context of digital technologies and human-computer interaction [21; 22].

More than viewing the development of tools based on urban systems data within a single one of these three frameworks, today's context has grown in complexity. This paper proposes to investigate this process through a combination of the three frameworks, viewing the development of data driven visualization tools for urban systems data at their intersection.

III. Case study Northeastern Energy Flows

A. *Campus as a city in a city*

In Spring 2015 the author carried out a studio project with a group of graduate students from the Master of Information Design and Visualization at Northeastern University. The goal was to valorize the data generated by the campus energy systems through the development of data visualization tools capable of providing better understanding and means for exploration of information contained within these data streams. Section III.C. discusses three of the projects developed by students as part of the studio led by the author.

The organizational structure and spatial organization of institutional buildings in the form of a campus somewhat represents a 'city within a city', a model of a comprehensive city (rather than a neighborhood, a campus of this kind resembles dynamics and structures of a city if we consider the governing and executive bodies such as president or faculty senate and the roles of mayor or city council, as well as the boundaries of infrastructure systems for transportation, energy, water, etc.). Specifically, the setting of Northeastern University's campus is urban and consists in 46 buildings spread out over 73 acres with a population of some 22,000 students, faculty, and staff. The campus is characterized by sophisticated energy systems due to the recent implementation of energy saving technologies and energy monitoring systems (in 2014, Northeastern ranked 3rd among 301 schools from 61 countries in the Green-Metric Ranking of World Universities). A growing number of sensors provide real-time monitoring of energy flows as well as readings of room occupancy (through motion sensors, CO2 sensors, and people counters at doors).

We engaged in several conversations with the University's Energy Manager who provided valuable insights into specific system setups, historic development, as well as workflow of stakeholders involved in the energy management. We started the project with a field trip through the various campus basements and rooftops in order to better understand the systems that ultimately generate the energy data we would later work with.

B. *Data types and system setup*

This case study documents a first phase of what is an ongoing research initiative. Additional types of data will be added over time, the types of data used in this first phase are indicated in TABLE I..

TABLE I. Data types used in project

Data type	Description
Electricity consumption	All 46 buildings are metered at 15 minute intervals and the data is accessed remotely through the campus-wide data management system. Period: 2012-2014
Building information	All 46 buildings are described in terms of surface area, number of floors, use type, year of construction, etc.
Planned classroom occupancy	Data indicating number of students in room as scheduled according to number of registered students for a class and room number of class. Period: 2012-2014
Climate data	Outdoor temperature, humidity, wind speed, cloud coverage, precipitation, etc. as measured at Logan Airport. Period: 2012-2014

To structure and manage the data for the data visualizations a mongodb database was created. MongoDB provides a Java MongoDB Driver which was used to connect to the database from within the Java based Processing IDE which was used to develop the data visualizations. From within the Processing environment, Javascript functions were used to execute queries to the MongoDB database. A Processing library was developed that contains a collection of classes and functions specifically written to facilitate the database access and queries and allow for more effective focus on the data visualization tool development themselves.

C. *Energy data visualizations*

Based on the system setup and data types described above a number of data visualization tools were developed. They all utilized the same types of data but focused on different aspects. It is a good example for how, by working with identical types of urban systems data, a manifold range of facets can be explored and information represented in a way that makes this same data meaningful for different contexts, purposes, and audiences having different goals and objectives.

The 'Pulse of an Arena' project (Skye Moret), Fig. 1, is based on initial analysis and an early insight of the unusual behavior of one specific building on campus: Matthews Arena. Opened in 1910, the arena is the world's oldest multi-purpose athletic building and houses the world's oldest artificial ice sheet [23].

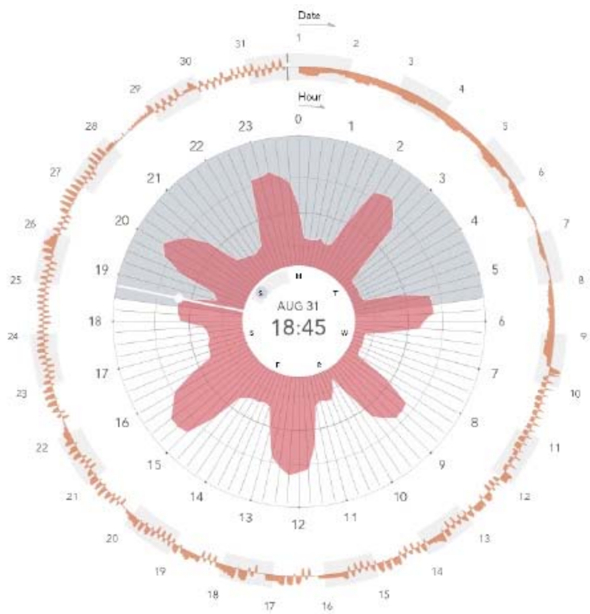

Fig. 1. 'Pulse of an Arena' project (Skye Moret).

It is used both for ice hockey as well as basketball and the continuous ice creation and ice melting together with rather dated energy and heating/cooling systems contributes to the building presenting the most irregular energy consumption behavior on campus. The visualization maps consumption levels as a polar line chart with an outer circle indicating consumption levels for an entire month and the inner circle detailing the same values on an hourly scale for one day. The circular sector shaded in gray indicates night time hours and adjusts dynamically for every day of the year. Concentric circular background lines are used to indicate daily mean and standard deviation. The resulting visualization tool provides access to the data in a rather intuitive way, conveying somewhat a 'pulse' of the building at a higher level as well as allowing for more detailed analysis at closer inspection.

The 'Energy Data Rings' (Xiaxin Chen), Fig. 2, and 'Campus Energy Consumption by Building Use Type' (Xuan Zhang), Fig. 3, projects both focus on facilitating understanding of the aggregate energy consumption levels of buildings by their use type designation (classroom, administration, residential, etc.) which is provided as part of the energy data set. The two projects follow two distinct approaches however. Zhang's project maps values as dynamic stacked bar charts where the bars represent the total of any one use type category and the stack segments represent the consumption levels of individual building that make up these categories. The left circle indicates total campus consumption and observing this visualization dynamically over time provides real insight into overall consumption dynamic as well as changing use biases by buildings serving different functions. Chen's approach, on the contrary, is based on a geographic map representation that contextualizes individual buildings in their urban setting. The pie chart ring is used somewhat as an 'information lens' - dragging the map to locate any one building at the center of this lens unfolds detailed information about this building's energy consumption and also locates the building within the ring pie chart where each building's energy consumption is represented by one segment, color corresponding to use type category. The entire ring represents 100% of total campus energy consumption at any time. In its animation over time this visualization enables insights into each building's role within the larger campus structure.

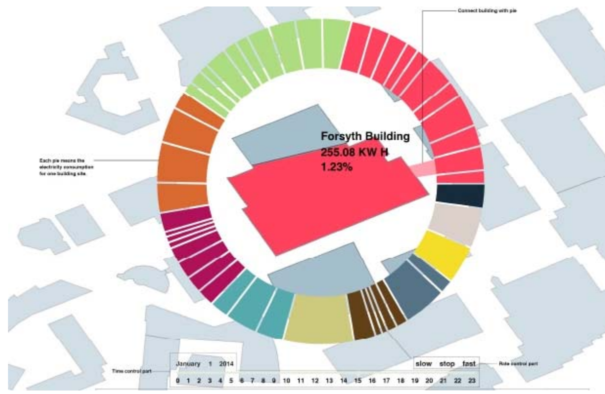

Fig. 2. 'Energy Data Rings' (Xiaxin Chen)

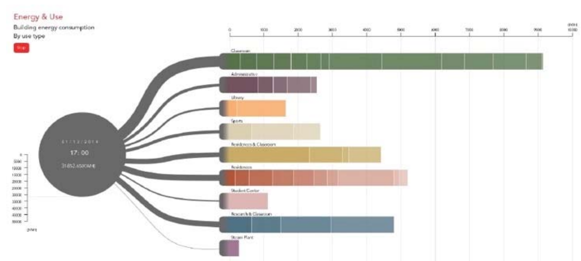

Fig. 3. 'Campus Energy Consumption by Building Use Type' (Xuan Zhang)

The 'Age and Energy' project (Xiangyi Fu), Fig. 4, is an exemplary case of how to bring out non-obvious facets when working with urban systems data. Having identified the presence of building construction year information within the available data, this project gives shape to a historic perspective on how the campus has developed over more than 100 years and proposes this interface for the exploration of energy consumption.

Fig. 4. 'Age and Energy' project (Xiangyi Fu)

An interactive time slider represents the over 100 years of existence of the campus and represents the various buildings at the year of their construction. By dynamically selecting a time range with the slider the map-based visualization provides information on the energy consumption level of the campus at that point in history. For the prototype energy data of 2013-2014 was used but the plan is to expand this to past decades digitizing paper documents about historic consumption levels.

D. *Data driven visualizations in the context of tool theories*

The projects described above are tools to explore urban systems data related to energy consumption. These tools visually represent data for meaningful access by different audiences (facility management, students, general public, etc.) and to facilitate action based on insights gained from the information represented. These data driven visualizations are tools, however, in a very different sense than mechanical tools used by an artisan, for example, or even software tools such as those used for word or image editing. A better understanding of the way in which they are tools, of the *nature* of them being tools, will help both in the analysis of existing data driven tools for urban systems as well as help chart the design space, for the development of future ones.

As an extension of man, these tools expand human senses, both in terms of quality and reach, as they translate imperceptible flows of electrical current in visual form that human sight and cognitive ability are capable of interpreting. These tools also extend human cognition and memory by the number and types of information that they are capable of bringing to a user's awareness simultaneously. Phenomena inscribed in data covering historic and up-to-the-minute events are made accessible and statistical operations enable aggregations and mathematical operations on large amounts of data too complex to achieve by man alone.

While these tools work *with* data, they are not *about* that data. Data in itself is an ideal illustration of the virtual as described by Levy. Data represents the result of the virtualization of actual events such as switching on the lights, turning on heating and cooling systems, using electric devices and machinery. Systems data resulting from these operations represent the energy consuming activities virtually. As in Levy's example of the seed and the tree, data from urban systems contain all the elements that are brought to surface by the visual data tools, yet these tools in a process of actualizing this potential can take on a multitude of different forms as has been illustrated by the case study. However, following Levy, tools themselves are virtualized actions that become actualized in every individual usage of the tool. In the work on data tools, as described here, there are then two levels of virtualization. The first is the transformation from actual events to resulting systems data. The second is the development of the data driven tools themselves, which virtualize the activities that the tools become part of (information seeking, measuring, probing, etc.). The actualization of the tools' potential then happens in two ways: when data drives the tool and when users purposefully apply it as part of their operations and in a specific situation and context.

To consider this context and situation in which tools are actually used is precisely the contribution of Activity Theory [16]. Data driven visualization tools are part of a larger, more comprehensive activity that goes beyond the mere work with the data and also beyond the sole user-device/interface interaction. In the case of energy data in an urban spatial setting such as a campus, this would include all the collaborative processes (planning/implementing of new campus buildings, building upgrades, purchase and allocation of electrical equipment, allocation of spaces and times for activities, etc.) that involve the stakeholders (facility department, utility providers, students, staff and administration, campus police and emergency care, etc.) related to providing for a well functioning energy system during ordinary operation, maintenance, emergency, etc. In the work on data driven tools, this viewpoint requires considerable attention due to the fact that work with data in a decontextualized manner is possible and too often the case, leading to operations on datasets without a clear perspective of real world collaborative contexts and situations. In our project, attention to this dimension was provided by a close collaboration and ongoing conversations with the campus energy manager as well as by an initial field trip through the campus basements and roof tops to explore all those instances (air conditioning units, chillers, boilers, pumps, etc.) where the energy system generates the data that composes the datasets we worked with. Finding and understanding the 'origin of data' is becoming of prime importance in this kind of operation and it will be so increasingly as data generating systems in urban environments grow increasingly complex. In this project, the exploration of the real-world context of the data generating energy systems and conversations with stakeholders involved in the operation contributed to identifying some key elements in the design and development work: the relevance of a map based interface to facilitate understanding by the professional as well as non-professional campus community; the focus on aggregating values by use type categories as particularly relevant for existing conversations and decision making processes; the highlighting of extreme values (such as in the case of Matthews Arena) as an effective tool to facilitate conversations to address inefficiencies in the system, the impact of building age on energy consumption.

IV. Discussion

The increasing pervasiveness of digital technology systems in urban environments is driving the generation of even larger amounts of data. While this poses a stress on traditional computational tools, it also affords the development of entirely new typologies of tools that can provide access to information based on this data in new forms and modalities for new user groups. Dynamic and interactive visual representations of urban systems data has proven an increasingly effective approach to valorizing this kind of data and to develop tools for understanding and action [24].

The development of urban data driven visualization tools is still in its infancy and this paper proposes a viewpoint based on some of the established tool theories in order to inform the analysis and the development of such tools. While each of the three theories employed captures a particular facet of the topic, a combination of the three views seems effective to tackle the issue more comprehensively. While this approach provides a more complete view on the projects presented as case study, data driven tools behave very differently from mechanical and physical tools which are the original focus of the discussed theories and this might pose some limitations.

Data driven software based tools are in a constant process of change. Modifying code is more feasible than changing the shape and mechanisms of a physical tool in production. So, while a hammer represents the virtualization of an action that becomes actualized every time a hammer is put to use in a specific situation and context, a data tool undergoes continuous cycles of virtualization and actualization as it gets updated, modified, re-developed, etc. in response to the experience of users during concrete operations.

The question of tool mastery in the context of digital tools has already been raised [25]. While mastery of a tool used to require a level of permanence in the tool configuration, software tools' rapid changes challenges this perspective on practice and tool usage. As digital technology networks increasingly pervade the built urban environment this condition of continuous data driven change enters a domain that used to be associated with a condition of permanence and slow change. This phenomenon will impact tools such as the ones discussed in this paper and will raise the question of what tool mastery can signify in this context.

Looking ahead, I see future work on systems such as those described in the case study section to focus on the integration of a more diverse set of data types including user generated data and content. This will offer new challenges both to the system as well as the information visualization side. Furthermore it will offer the opportunity to explore how the viewpoint based on the presented three tool theories holds up to this and succeeds in informing the development of urban data driven visualization tools.

V. CONCLUSION

This paper proposes a tool theory based viewpoint for the analysis and the design of dynamic visual tools based on urban systems data. As pervasive digital technology networks in urban environments generate increasing amounts of data in real time, there is an increasing potential for new use scenarios and tools based on these data streams. Frameworks for the analysis and the development of such new tools though are still in their infancy and this paper proposes a trifold approach based on three key tool theories to better grasp the nature of these new tools.

A case study is presented in which urban energy systems data is used as a basis for the development of data driven visual tools for understanding and action based on information derived from the data. This project is then analyzed in light of the tool theory framework.

While this approach enables a deeper understanding of the subject, there are challenges linked to the transient nature of data driven software based tools in the context of urban environments. The ongoing cycle between tool use and (re-)development based on the ease of code adaptation is in stark contrast to the character of *permanence* of traditional mechanical tools and also of a common idea of the built urban environment. This dichotomy between *permanence* and *change* at the intersection between the physical and the digital in the context of digitally augmented urban environments provides an interesting and relevant ground for further exploration.

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