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# A SYSTEMATIC LITERATURE REVIEW OF GREEN SOFTWARE DEVELOPMENT IN COLLABORATIVE KNOWLEDGE MANAGEMENT ENVIRONMENT

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## Abstract

**Background:** Main asset in software industry is knowledge of employees who work in software development. Knowledge is main asset to succeed in green sustainable development. There is no research about to implement techniques of Knowledge Management (KM) in order to help in managing knowledge of Green Software Development (GSD). This is the research gap.

**Aims:** This paper assesses literature on GSD in regards to the evolution of green computing, and discusses about how KM comes in to assist in managing the knowledge of GSD.

**Method:** This study reviews current status of GSD by using tertiary study to review articles. A standard systematic literature review method is carried out to employ a manual search. Focus domains, knowledge areas and measurements of GSD will be identified so that can distill a common understanding of the state-of-the-art GSD. Then, discussion about how KM comes in to assist CoP in managing their knowledge of GSD will be carried out in detailed.

**Results:** 37 articles are chosen as primary studies. Among all focus domains, GSD life cycle gains highest interest. Knowledge area of energy efficiency receives the highest attention. Measurement for power consumption obtains the greatest priority to measure "greenness" of software developed.

**Conclusion:** Focuses covered by GSD are limited. Researchers are encouraged to study about diverse areas of GSD. Our future work is to develop model of GSD which involving KM process to ensure members of CoP in software environment able to manage their knowledge and sustain best practices of GSD for the future.

## Introduction

Green Software Development (GSD) is a methodical process which allows a systematic, disciplined and well-organized development of green software products. On the other side, Knowledge Management (KM) is a cyclic process with a set of activities, techniques and practices that will simplify the process of capturing, creating, storing, distributing and sharing tacit and explicit knowledge. The main asset in software industry is the knowledge that held by employees who develop software products. Moreover, knowledge is also becoming a significant intangible asset to achieve success in the matter of green sustainable development. As far as we know, there is no research about to implement concepts and methods of KM in order to facilitate effectiveness in managing knowledge of GSD. Therefore, there is a research gap on applying KM in GSD industry in order to assist Community of Practice (CoP) in managing their knowledge.

The objective of this paper is to identify GSD in regards to the evolution of green computing, and then how KM comes in to assist in managing the knowledge of GSD. So that, the experts, researchers and software developers can share their experience, insight, techniques and environmental knowledge about GSD with the aim of producing greener software products that able to sustain the environment and also the future generation. In order to achieve this goal, the first step is to perform a systematic review about GSD. According to [1], it is important to carry out systematic review so that new inception of innovative thoughts and findings able to be identified and used for further researches.

Chapter 2 will identify previous works from various researchers about definition of green computing, definition of green software and GSD, definition of KM, the ways of KM concept is applied in different green industries; and the matter of software development in KM environment. Then, on Chapter 3, research gap and research questions are being highlighted. For the search strategy of this paper, Chapter 4 will describe it clearly. At first, database searched is carried out by identifying appropriate keywords to carry out the search. Inclusion and exclusion criteria for the searching of papers are being recognized concisely. Next, on Chapter 5, the search results will be analyzed in order to discover the trends of research about GSD: Focus domains, knowledge areas and measurements that have been currently concentrating on. Therefore, we can distill a common understanding about the state-of-the-art GSD. Moreover, since we explain on Chapter 2 about how KM concept can be applied in software development, and also be applied in green and sustainable development, then on the Chapter 6, we will discuss

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briefly about how KM comes in to assist in managing the knowledge of GSD. Finally, Chapter 7 is the overall conclusion of this paper.

# Previous Research

## A. Green Computing

According to World Business Council for Sustainable Development, the concept of "eco-efficiency" and AGENDA 2050 recommend that new prospect for business with long-term view on a sustainable development should be proposed [2]. IT infrastructures, such as datacenter facilities and hardware, lead to different environmental problems during its production, operation, application and disposal too [3]. Hence, [3] appealed that IT-related community is ethically, legally and socially required to green the IT applications, practices, products and services. Besides, data center architect of Teradata, [4] had also the same opinion about green computing is both significant business and ethical question currently.

The general definition of green computing is to support business essential computing demands with minimal possible amount of power consumption and finally achieve sustainable computing [5]. Moreover, Table 1 will show the detailed definition of green computing by different researchers.

**Table 1. Definition of Green Computing**

| Author | Definition |
|---|---|
| [6] p. 191 | "The environmentally responsible design and use of computer equipment, information and communication technologies, and include the implementation of energy-efficient central processing units, servers, peripherals, etc. as well as reduced resource consumption and proper disposal of e-waste". |
| [7] p. 231 | "A global concept that entails system architecture, system software, parallel and distributed computing network… aims to reduce power consumption of computer systems, provide high-efficient, dependable and pervasive services, and achieve the objective of low power of IT systems". |
| [8] p. 1 | "Practice of using computing resources more efficiently while maintaining or increasing overall performance… Efforts to reduce energy costs while improving performance of data centers and desktop computers… to control and reduce environmental footprint of computing by minimizing use and discharge of hazardous materials, conserve water and other scarce resources and reduce waste throughout value chain… and to improve product and service design, rethink value chain 4.and reengineering IT processes". |
| [9] p. 136 | "Study and practice of using computing resources efficiently and that the main objective is to minimize the pollutions of environment". |
| [3] p. 25-26 | "Known as Green IT too… Study and practice of designing, manufacturing, using and disposing of computers, servers and associated subsystems-such as monitors, printers, storage devices, and networking and communications systems-efficiently and effectively with minimal or no impact on the environment… also strives to achieve economic viability and improved system performance and use, while abiding by our social and ethical responsibilities". |

In conclusion, green computing is a model that includes study and practice of IT-related architecture, hardware, software, networks, systems and processes, in order to governor the environmental carbon footprint by using the computing resources effectively and efficiently with minimal negative effect to the environment, in the mean while without compromising the economic productivity and social responsibility in the long run. GSD is only one of the detailed parts of green computing. Over the last decade, first wave of green computing had been emphasized on cost minimization and environmental negative influences of datacenter facilities; these days, the emphasis is on innovation and changes that are required in IT community so that can integrate green computing with global sustainability in order to produce more intangible green benefits to the sustainable IT environment in the long term [8]. Today, global effort on the movement of green computing is strongly needed to promote sustainability [4].

## B. Green Software and Green Software Development (GSD)

In general, green software is defined as software which offers direct and indirect positive effects to the economy, society and environment subjects from its development life cycle and usage [10]. The researchers narrowed down the definition and defined green and sustainable software is: Software which focuses more in environmental requirements. Moreover, green and sustainable software measures, evaluates and maximizes the optimization of direct and indirect consumption of natural resources continuously in development phase. Therefore, the software products can reduce depletion of natural resources and energy, and also minimize the direct and indirect negative impacts to the environment.

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Other researchers divided the impacts into three: First-order impacts or impacts of ICT supply, which are impacts that directly affect power consumption or natural resources, such as hardware requirement, performance requirement, software product packaging, network bandwidth etc.; Second-order impacts or impacts of ICT usage, which are impacts that evolve from the usage of services offered by the software itself; Third-order impacts or systemic impacts of ICT, which are impacts that caused by diverse interdependent systems that trigger rebound influences. For example if more natural resources are used to produce one specific type of software, but the same amount of resources can produce more of other types of software, then it creates extra demand for these resources [11] [12].

There is a difference between green software and green by software. Green software is software that runs on environmental sustainable manner, with the aim of producing as little as environmental waste and energy consumption as possible in the whole software development life cycle and operation [13]. On the other hand, [13] defined that green by software is the use of applications, methods with the intention of producing as little as environmental waste and energy consumption as possible by means of IT.

GSD is a methodical process which allows a systematic, disciplined and well-organized development of green software products. It includes few phases: Requirement-Gathering, Design, Implementation, Testing, Deployment/ Installation, Maintenance and Retirement [14]. Programmers need to be coached about the environmental sustainability concerns. Therefore they will be aware of the environmental issues and always write energy efficient code while developing software [15]. [16] developed a GSD Model that suggests various significant practices in different phases of software development life cycle that able to provide recommendations in developing software program in a more environmental friendly path. Moreover, [13] also proposed a list of methods about how to produce green software products.

## C. Knowledge Management (KM)

KM is a cyclic process with a set of activities and practices that will simplify the process of capturing, creating, distributing and sharing knowledge [17]. The researchers explained that there is a shift in the emphasis of KM. At first, KM emphases on technical aspects and tools, for example Management Information System (MIS) and so on, which are about how to capture and share knowledge with the technical tools. Then, emphasis of KM changes to pay more interest on socially embedded phenomena, such as solutions for complex human systems and CoP. The members of CoP develop own practices, conventions and routines, then share among themselves.

Techniques of KM can be applied in organizational learning, where members in an organization share expertise, insight and culture of the organization. However, employees in the organization should accept new knowledge, experience and culture openly and without bias, in order to make sure the process of organizational learning can be effective [18]. Effectiveness of managing the intellectual capital of an organization can help employees in making better and timely decisions in order to resolve problems [19]. If the intellectual capital is just being saved in organization memory without delivering and sharing to the employees who truly need it, then it is useless. Organization memory is computerized database that stores intellectual capital (knowledge captured) of the company [20]. The knowledge of organization can be shared through networking, which involves active collaboration and interaction within and between the employees with the aim of sharing tacit knowledge [21].

According to the result in the study of [22], small and medium size organizations (SMEs) are knowledge users rather than knowledge producers. Moreover, the SMEs do not have extra resources to build up a knowledge-based system. Hence, it is very crucial that to have a knowledge base which allows external web-based access and enables the external experts and researchers in the same industry to share their expertise and best practices with the SMEs.

Nowadays, advanced Information and Communication Technology (ICT) offers various solutions to perform collaborative KM. Collaborative KM is the most proper way to capture project-based knowledge [23]. The researchers mentioned that there are two categories of collaborative KM for companies. The first category is channels, such as emails, document management system and so on, which degree of commonality is low and content can be generated by anyone. The second category is platforms, such as intranet, extranet, which information is created by a selected group of people and then made widely accessible. Moreover, according to [23], the rapid emerging of Web 2.0 initiates the collaborative technologies and affects the industries significantly on how to manage knowledge of their employees.

## D. KM in Green Industries

Today, knowledge becomes the main asset to succeed in the combinatorial area of environmental, economic and social sustainable development [24] [25]. Techniques of KM have been applied in green and sustainable development of

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different industries. For example, in waste management industry, there is a paper that applies KM techniques in the planning of sustainable waste management system in City of Gothenburg, Sweden [26]. Moreover, there is another paper that proves that how institutional knowledge can be managed with the application of KM in a case study on greywater reuse in Jordan [27].

Furthermore, there are several papers that focus on examining methods to capture, sustain and share knowledge in the area of sustainable construction [22] [28]. The researchers stated that it is very popular to implement tools of KM for knowledge creation within a sustainability context in order to achieve healthier construction industry that based on efficient use of resources and ecological principles, without compromising the creation of built environment with an improved quality of life.

On the other hand, a hybrid methodological framework is suggested by [29] for monitoring and assessment of land degradation in sustainable land management sector. The framework applies KM approach to incorporate local knowledge, expert knowledge, field-based data and remotely sensed data sources from local to national and international scales so that able to assist land managers and policy makers in enhancing the sustainability of land management.

In sustainable tourism planning sector, research proved that there is some difficulties in integrating the wealth of academic knowledge about sustainable development principle that resides within universities and government effectively to those who actually plan, decide and manage sustainable tourism activities that mean for their community [30]. Therefore, the researcher suggested that KM approach can be implemented as a bridge and solution to integrate this knowledge-practice gap. [31] also mentioned that the wider and trans-functional integration capabilities of KM integration can be a success in integrating different sources of information.

As mentioned in previous paragraph, KM integration is vital, regardless of industry. Therefore, it is important to improve the effectiveness of integrating knowledge to action, with the objective of applying concepts of KM to harness science and technology for sustainability. As proposed by [32], there are three features of "boundary management" which can integrate knowledge to action for sustainable development: Communication, translation and mediation.

[32] further explained that communication cannot be in one-way, which experts assume that they understand the problems that faced by decision makers. On the other side, decision makers also assume that their problem will be answered by the experts. Therefore, close engagements, such as regular meeting and workshops, are strongly needed between experts and decision makers. The second feature, translation, can enable mutual comprehension and information flow between experts and decision makers although they may separate by different language, presumption, background, jargon, norm and experience. Furthermore, active mediation activities, such as to enhance legitimacy, increase transparency, provide rules of conduct, reveal all perspectives and establish decision-making criteria, able to minimize conflict between experts and decision makers. Finally, success can be obtained in linking knowledge to action for sustainable development.

Concept of Environmental KM (EKM) that introduced by [33] and [34] is defined as management of knowledge with the use of technology, mechanisms, policies, people, tools, processes, structures, and strategies in order to capture, store, transfer and retrieve environmental knowledge with the aim of decreasing environmental negative impacts. EKM becomes a useful KM system to manage environmental knowledge so that organizations can gain business and also environmental sustainability.

[35] proposed Environmental Knowledge Circulation Process (EKCP), which is a combination of the concept of environmental management and knowledge circulation process (KCP), with the objective to assess performance of organizations in managing environmental knowledge. It consists of five phases, from knowledge creation, accumulation, sharing, utilization and lastly internalization. Result of their research presents that efficient EKCP can improve both environmental and financial performance of the organizations and finally attain a win-win situation.

[26] mentioned that in order to achieve sustainable development, manage different knowledge areas in a more structured and organized manner becomes an essential activity in planning and decision-making processes. On the other hand, systematic and structured management of environmental knowledge can collect different individual expertise and store in a standardized format, which allows sharing of the environmental best practices becoming easier, then indirectly encourages continuous learning in environmental practices, promotes environmental awareness and nonstop environmental improvements by placing greater emphasis on green product development [31] [35].

Result of the empirical study of Mohamed, [24] showed that KM is important in the contribution to sustainable development, particularly in the efficient use of resources. Moreover, many organizations are moving forward with green differentiation strategy and developing environmental-friendly products which may create a considerable market. Hence, [35] concluded in their study that environmental knowledge is becoming a value intangible asset in the contribution to sustain green competitive advantage in green business. Other researchers also agree that significant role of KM in generating sustainable competitive advantage to the companies [31][36] [37].

One of the goals of KM concept is to share knowledge without the limitation of geographic boundaries. Furthermore, [38] indicates that a lot of sources of information and perspectives need to be shared within different parties in the world in order to find solutions that will guide them for moving forward together to a more environmental-friendly environment. Therefore, mobilization of knowledge that relates to sustainable development activities across the world is strongly essential which able to boost up knowledge and experience sharing among various development teams in an industry [24].

### E. Software Development in KM Environment

Software development (or software engineering) is about concerning of theories, practices, methods and tools that are essential to develop and maintain the immaterial software products [39]. The main asset in software industry is the knowledge that held by the employees who develop software products [40]. Hence, software development is a knowledge-intensive process and it is important to manage the knowledge effectively so that software organizations can reduce cost and time, enhance quality and make better decisions in software development process [21] [39] [40] [41]. On the other hand, [42] concluded that in 21st century, if software companies want to achieve success, they should integrate technology with social collaboration and become continuous learning software organizations.

It is important to create organizational knowledge in process of software development in order to make a success [40]. [20] introduced "experience factory" for software development industry, which is a KM infrastructure that will gather all the experience from software development projects, then package them in a standardized format and store them in an experience base of the company. Therefore, the collected experience can suggest improvement to the new software development projects in future.

Two approaches can be applied in software development, which will also influence how knowledge is being managed [43]. The researchers explained that the first approach is traditional development method, for example waterfall process, which primarily depends on managing explicit knowledge. On the other hand, the second approach is by applying agile development process, which is mainly focusing on KM actions that are related to tacit knowledge.

There are two methods of knowledge delivery: "pull" method and "push" methods [44]. The researchers clarified that pull method is about employees already know types of knowledge that they need, and they will search for the knowledge by themselves; while push method is about delivering knowledge to employees without prior interaction. Based on result of research carried out by [19], pull method of knowledge delivery will be more effective if applying in software development projects. Moreover, the result shows that SMEs in software development industry are more likely to apply pull method for knowledge delivery. Furthermore, the researchers conclude that if the knowledge needed able to be delivered close to the time that the software developers need it, then efficiency of software development can be increased.

According to longitudinal study that carried out by [21], KM methods for software development perspective can be applied as an answer to perceived problems in the current software practices; as a support for planning future software projects; and as a warehouse for codifying new knowledge based on experience that earned in current software development. Hence, the new experience and lesson gained can be shared among software developers.

## Research Gap and Questions

There is a research gap in current literature about applying KM in GSD industry in order to assist CoP in managing their knowledge. Hence, the aim of this paper is to discover the trends of GSD in green computing literature, and then classify them into different focus domains, knowledge areas and measurements. Next important step is to explain clearly about how KM comes in to assist in managing the knowledge of GSD. Hence, research questions of this study are:

RQ1. How much GSD has been there?
RQ2. What focus domains of GSD are being addressed?
RQ3. What knowledge areas of GSD are being discovered?
RQ4. How many measurements for GSD are being studied?

## Method

### A. Database Searched

The electronic database search process in this work is a manual search of journal papers and conference proceedings by identifying as relevant to information technology and

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computer science. The selected journals and conferences are shown in Table 2.

**Table 2. Data Sources**

| Data Source | Acronym |
|---|---|
| 23rd International Workshop on Power and Timing Modeling, Optimization and Simulation | PATMOS 2013 |
| 26th International Conference on Software Engineering and Knowledge Engineering | SEKE 2014 |
| 2nd International Workshop on Green and Sustainable Software | GREENS 2013 |
| 3rd International Conference on Computational Sustainability | CompSust'12 |
| Electronics Goes Green 2012 | EGG 2012 |
| Environmental Impact Assessment Review | EIR |
| First International Workshop on Green and Sustainable Software | GREENS 2012 |
| IEEE 11th International Symposium on Intelligent Systems and Informatics | SISY 2013 |
| IEEE 3rd International Conference on Cloud and Green Computing | CGC 2013 |
| IEEE Conference on Open Systems | ICOS |
| IEEE India Conference | INDICON |
| IEEE International Conference on E-Business Engineering | ICEBE |
| IEEE Symposium on Computers and Communication | ISCC |
| Information and Software Technology, Elsevier | INFSOF |
| Integration of Environmental Information in Europe | EnviroInfo |
| International Journal of Computer Trends and Technology | IJCTT |
| International Journal of Software Engineering and Its Applications | IJSEA |
| International Symposium on Humanities, Science and Engineering Research | SHUSER |
| IT Pro, IEEE Computer Society | IEEE CS |
| Journal of Cloud Computing: Advances, Systems and Applications | JoCCASA |
| Proceedings of the 10th International Conference on Advances in Mobile Computing and Multimedia | MoMM2012 |
| Proceedings of the 18th International Conference on Evaluation and Assessment in Software Engineering | EASE' 14 |
| Proceedings of the 2013 International Workshop on Software Development Lifecycle for Mobile | DeMobile 2013 |
| Proceedings of the 28th Annual ACM Symposium on Applied Computing | SAC 2013 |
| Proceedings of the First International Conference on Information and Communication Technologies for Sustainability | ICT4S 2013 |
| Proceedings of the Fourth Asia-Pacific Symposium on Internetware | Internetware'12 |
| Proceedings of the Third International Workshop on Requirement Engineering for Sustainable Systems | RE4SuSy 2014 |
| Software-Practice & Experience | Softw.Pract.Exper. |
| Sustainable Computing: Informatics and Systems | SUSCOM |
| The First International Conference on Green Computing, Technology and Innovation | ICGCTI 2013 |

## B. Inclusion and Exclusion Criteria

A number of inclusion criteria and exclusion criteria are specified in order to select appropriate and relevant papers as primary studies in this review work.

Inclusion Criteria
1. Published papers that written in English language.
2. Published papers with the exact phrase of "green software development" that appears either in the title or in the article itself, without limitation of year of publication.
3. Published papers that are in the form of scientific paper, for example papers that are published in journals of conference proceedings etc.

Exclusion Criteria
1. Published papers that written in languages other than English language.
2. Published papers with the exact phrase of "green software development" that do not appear either in the title or in the article itself, without limitation of year of publication.
3. Published papers that only focus on green IT as a general, without focusing on GSD.
4. Published papers that are not in the form of scientific papers, for example notes, news, collection of abstracts, letter, patents, oral presentation, erratum or citation.
5. Duplicate papers with the same contents, but published in different places.

# Results

## A. How much GSD has been there? (RQ1)

There are 44 results shown. We select 37 of them as primary studies, which are compliant to the predefined set of

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inclusion and exclusion criteria. Summary of the 37 articles that include in this GSD literature review is shown in Appendix.

## B. What focus domains of GSD are being addressed? (RQ2)

Table 3 shows various focus domains of researches about GSD from year 2010. Total there are 37 papers which have been chosen as primary studies for this systematic literature review. Each of the selected paper as primary studies is only been categorised into one focus domain. Due to the completion date of our systematic review, the search process of papers as primary studies of this work is only carried out until September 2014.

Looking at the research papers by year of publication, we notice that there is an increasing interest in the area of GSD from year 2010 and reaches a peak during year 2013. However, since our systematic review is conducted in October this year, hence our covering only the first three quarters of year 2014. Therefore it is incorrect to say that there is a decrease in attention from year 2014.

Besides, as shown in Table 3, there is one paper which has been categorised to column of year 2015 because this specified paper is set to be published in a journal of year 2015. Among all the focus domains, software development life cycle is paid the highest attention in order to create environmental-friendly and sustainable software products. Next is focus domain of software metrics, which able to measure the "greenness" of software products, receives the second highest interest from the researchers. There is only one publication has been classified into focus domain of software definition approach and software for digital media platform.

**Table 3. Distribution of Publication According to Focus Domains of GSD**

| Focus Domains of GSD | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
|---|---|---|---|---|---|---|---|
| Application Software | | 1 | 1 | 2 | 1 | | 5 |
| Environmental Management for Software Company | | | 1 | | 1 | | 2 |
| Software Definition Approach | | | | 1 | | | 1 |
| Software Development Life Cycle | 1 | 3 | 1 | 4 | 1 | 1 | 11 |
| Software for Cloud Environment | | | | 2 | | | 2 |
| Software for Digital Media Platform | | | 1 | | | | 1 |
| Software for Legacy Systems | | | | 2 | | | 2 |
| Software for Mobile Platform | | 1 | 1 | 2 | | | 4 |
| Software Metrics | 1 | | 2 | 4 | 2 | | 9 |
| Total | 2 | 5 | 7 | 17 | 5 | 1 | 37 |

Application Software

Publications that introduce the development of "greenness" in application software which include end-user application software and system software will be categorized under this focus domain.

Environmental Management for Software Company

This focus domain discusses issues that apart from the technical perspective of GSD. There are ISO 14000 environmental management standards (for example, ISO 14040, ISO/IEC 14001 etc.) with the objective of supporting companies to regulate their operations in order to minimize negative environmental impacts [45]. These standards should put into practices of software development workflows so that able to produce green software products.

Software Definition Approach

There is only one publication has been classified into this focus domain, which deeply explains about commonly recognized definition and aspects of GSD.

Software Development Life Cycle

Software development life cycle is a methodical process which introduces a systematic, disciplined and well-organized development of a software product [14]. It contains various phases. Different important practices are presented in the phases that capable of assisting in developing software products in a more environmental friendly path [16].

Software for Cloud Environment

This focus domain is about combination of cloud computing and GSD structure in order to achieve the goal of energy efficiency.

Software for Digital Media Platform

Digital media software service is one of the significant parts of Information and Communication Technologies (ICT). However, there is a difference of aspects between green software and systems design of digital media compared to traditional software products [46]. Currently, there is only one publication has been classified into this focus domain.

Software for Legacy Systems

There are two publications that have been categorized into this focus domain. One of the papers introduces a migration process for an existing software system so that the system can receive higher energy efficiency, lower execution time and more sustainable new lease of life [47]. Another publication examines the trade-off between software functionality and power efficiency of the legacy systems [48].

Software for Mobile Platform

This focus domain discusses different methods and practices that can help in developing sustainable, environmental-friendly and energy-efficient application software for mobile devices.

Software Metrics

This domain focuses on introducing various metrics that related to software perspective which can help in measuring the "greenness" of software products.

## C. What knowledge areas of GSD are being discovered? (RQ3)

Table 4 shows different knowledge areas of current published papers about GSD from year 2010. It is highly possible that one paper is discussing more than one knowledge areas. However, since this review is performed in October this year, hence our covering only the first three quarters of year 2014. Therefore it is improper to say that there is a reduction in interest from year 2014. Besides, as shown in Table 4, there is only one paper which has been categorised to column of year 2015 because this specified paper is set to be published in a journal of year 2015.

Among all the knowledge areas of GSD, area of energy efficiency receives the highest priority from the researchers. Besides that, the various software development phases from software development life cycle receive high interest too, especially the design phase, implementation phase, requirement phase and testing phase of green software. Then, software quality is also receiving high attention from the current researchers. It is important that while increasing environmental sustainability of software products, in the mean while software quality cannot be compromised.

**Table 4. Knowledge Areas of Current Published Papers about GSD**

| Knowledge Areas of GSD | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
|---|---|---|---|---|---|---|---|
| Analytic Network Process | | | | 1 | 1 | | 2 |
| Carbon Emission/ Footprint | | | | 5 | | | 5 |
| Energy Efficiency | | 2 | 4 | 12 | 1 | | 19 |
| Green Compiler and Scheduler | | | 1 | | | | 1 |
| Impacts on Natural Resources | | 2 | | | | | 2 |
| Infrastructure for Developing Software | | 1 | | | | | 1 |
| Internetware | | | 1 | | | | 1 |
| Measurement - Black Box | | | 1 | 1 | | | 2 |
| Measurement - White Box | | | 1 | | | | 1 |
| Recommended Actions and Tools | | 2 | | 2 | 1 | | 5 |
| Simulation and Modelling | | | | 4 | | | 4 |
| Software Development Phase of Deployment/ Installation | 1 | 1 | | | | | 2 |
| Software Development Phase of Design | 1 | 2 | 1 | 4 | | | 8 |
| Software Development Phase of Implementation | 1 | 2 | | 4 | | | 7 |
| Software Development Phase of Maintenance | 1 | 1 | | 4 | | | 6 |
| Software Development Phase of Requirement | 1 | 2 | | 4 | | | 7 |
| Software Development Phase of Testing | 1 | 2 | | 4 | | | 7 |
| Software Process Doc- | 1 | | | 1 | 1 | | 3 |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| umentation | | | | | | | |
| Software Process with Agile Method | 1 | | | 2 | | 1 | 4 |
| Software Process-Centric Perspective | | | 1 | | | 1 | 2 |
| Software Product - Distribution | 1 | 2 | | | | | 3 |
| Software Product - Retirement/Deactivation/ Disposal | 1 | 3 | | 1 | | | 5 |
| Software Product - Usage | 1 | 2 | 1 | 1 | | | 5 |
| Software Quality | | 1 | 1 | 2 | 1 | 1 | 6 |
| Web Ontology Language (OWL) | | | 1 | | | | 1 |
| Total | 11 | 25 | 13 | 51 | 5 | 3 | 108 |

## D. How many measurements for GSD are being studied? (RQ4)

In order to measure effectiveness of KM in assisting CoP to manage their knowledge of GSD, there is a need to link KM initiative to environmental sustainability and green software quality so that it is able to help in justifying KM to senior management, member of CoP, software developers and other stakeholders. Therefore, it is able to improve the ability to manage and share knowledge of GSD effectively. Below is Table 5 that shows different measurements of current published papers that are applied in GSD. These measurements are used to measure effectiveness of the green software so that environmental sustainability can be achieved without compromising the software quality.

Among the measurements for measuring software quality, both functionality and performance receive the highest priority in measuring the quality of green software. Functionality is about resources of the software used in order to achieve specific functions; while performance is the period required for responding to requests of users. However, dissimilar functional types of applications may have different grade of power efficiency. Then, the second highest priority is accessibility, modifiability and usability. Accessibility is about capability to serve user regardless place, hardware technology used, background or experience. It is the degree to which a software is available to people. Modifiability is the capability to adapt changes quickly and cost effectively. Usability is the characteristics of being user-friendly and ability of software to maintain its service delivery under specified conditions for specified time period. Next, both portability and reliability obtain the second lowest attention from the researchers. Portability is the capability to run under diverse computing setting. Reliability is about entirety of necessary functions that software can deliver. Lastly, researchers pay the lowest interest on the measurement for adaptability and supportability. Adaptability is possibility of software to be adapted for specific users' needs, while supportability is about the capability to be easily maintained after installation.

On the side of environmental sustainability, measurement for power consumption, total of electricity consumption during software development process, receives the highest attention in order to measure the "greenness" of the software developed. The next is carbon footprint, which gains the second highest interest from the researchers. It is about the amount of regular carbon dioxide ($CO_2$) emission during software development life cycle. Then, measurement for green energy usage (use of renewable energy) obtains the second lowest attention from the researchers. However, current papers pay the lowest priority on projects' footprint, which about environmental effects produced during software development process, and reusability, which about degree for reusing in other systems or hardware.

**Table 5. Measurements of Current Published Papers that are applied in GSD**

| Measurements of GSD | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
|---|---|---|---|---|---|---|---|
| Green Software Quality | | | | | | | |
| Accessibility | 1 | 2 | | | | | 3 |
| Adaptability | | | 1 | | | | 1 |
| Functionality | | 1 | | 2 | 1 | | 4 |
| Modifiability | 1 | | | 1 | | 1 | 3 |
| Performance | 1 | | | 2 | 1 | | 4 |
| Portability | 1 | 1 | | | | | 2 |
| Reliability | | | | 1 | 1 | | 2 |
| Supportability | 1 | | | | | | 1 |
| Usability | 1 | | | 1 | 1 | | 3 |
| Environmental Sustainability | | | | | | | |
| Carbon Footprint | | | | 2 | 2 | | 4 |
| Green Energy Usage | | | | 1 | 1 | | 2 |
| Power Consumption | | 2 | 2 | 6 | 2 | | 11 |
| Projects' Footprint | 1 | | | | | | 1 |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Reusability | 1 | | | | | | 1 |

# Discussion

This review focuses on current research status of GSD: focus domains, knowledge areas and measurements of GSD. There are total of 37 published papers are identified by using our search terms, which are confirmed out that interest on GSD from researchers is growing, especially achieves the peak in year 2013. However, there is still a lot needed to be discovered in GSD area. The vast majority of these papers focus on green software development life cycle and also the green metrics. These may due to the life cycle and metrics are the main components in the process of developing green software. The software development life cycle consists of significant and crucial phases which uncover important issues in the early stage that are essential for software developers to make sure that the software developed is able to meet the needs of stakeholders. On the other hand, focus domain of software metrics is the second highest important in GSD which can help in measuring "greenness" of software products. This is because software metrics are strongly required in order to make sure that software development companies are delivering what the stakeholders really need. The metrics of GSD are used to measure effectiveness of the green software so that environmental sustainability can be achieved without compromising the software quality.

Knowledge area of energy efficiency gains the greatest priority from the researchers. Energy efficiency is one of the most direct measurements to slow down the energy demand growth and measure whether the software is achieving environmental sustainability. It can be more than one metrics to measure the energy efficiency of software system because software consists of diverse modules with different purposes. Moreover, the various software development phases receive high interest too. This is due to by improving the green practices in individual phase of software development life cycle can contribute to the quality of environment in long-term basis. Besides, by introducing the best practices, policies, guidelines and recommendations phase-by-phase to the members of CoP is able to allow them in observing sustainability-related effects on each phase of life cycle of software before continuing to the next phase. On the other hand, measurement of power consumption receives the highest attention in order to measure the "greenness" of the software developed. Software does not consume the power directly because it runs on the hardware resources. However, software with higher complexity definitely will consume more power. For example, highly dependent modules can result in high power consumption. Therefore, software developers should collect requirements of the software precisely and make sure the software developed is enough to serve the users' needs without compromising on environmental sustainability.

As we mentioned earlier, the main asset in software industry is knowledge that held by employees who are involving in development of software products. Moreover, knowledge is also the main asset to succeed in the area of green sustainable development. Many organizations are moving forward with green differentiation strategy and developing environmental-friendly products which may create a considerable market. Environmental knowledge is becoming a value intangible asset to manage wisely in the contribution to sustain green competitive advantage in green business. However, there is no research that applying KM in GSD industry in order to assist members of CoP in managing their knowledge of GSD. Techniques of KM already have been applied in green and sustainable development of different industries. Therefore, KM should also be able to apply in GSD area. From the sustainability viewpoint, KM techniques can be useful in software development industry as a way to capture, gather, store, retrieve, share and apply tacit and explicit knowledge of GSD from different sources for the purpose of achieving reduction in energy consumption, carbon dioxide emission, waste of resources, global warming, projects' footprint and various pollution in the software development phases. The KM approaches and activities can be implemented as a bridge and solution to integrate this knowledge-practice gap and become an essential part in planning and decision-making processes of software development. Hence, software developers can reduce cost and time, enhance software quality and make better decisions in software development process. At the end, software development companies can achieve environmental sustainability in long-term basic.

The wider and trans-functional integration capabilities of KM integration can be a success in integrating different sources of information. At first, knowledge of GSD that only retains in particular IT experts, individuals or researchers should be converted into actionable knowledge through KM techniques. For example, knowledge base can help in capturing and then storing the knowledge in a standard and appropriate format which can be accessed by all the members of CoP at the right time and in the right place. Therefore, knowledge about how to exercise various green practices and recommendations in the process of developing software can be revealed and shared among all software developers. The standardized knowledge allows sharing of the environmental best practices becoming easier, and then indirectly encourages continuous learning in environmental practices. The tacit knowledge becomes "actionable" while it is shared and collaborated among members of CoP in software industry and finally it is able to answer the right questions so that positive influences can be delivered to the company, the

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environment and also the society. Moreover, the collected experience that stores in KM infrastructure can suggest improvement to the new software development projects in future. In short, application of KM in software development industry can provide an action-oriented and collaborative approach to transform existing knowledge of experts and researchers into more "actionable" knowledge to the real world.

## Conclusion

The research papers that are included in this literature review provide a snapshot on focus domains, knowledge areas and measurement of GSD which is representative of the state of the art at the time. However, this study suffers from certain limitation. In particular, we have restricted ourselves to a manual search of international journals and conferences only. Currently, the spread of focuses covered by current GSD are limited. Although green computing is widely been covered by numerous researchers, and there are various solutions and tools that study on methods of energy efficiency and carbon dioxide emission reduction on hardware development. However, the area of GSD is just beginning in this industry. There is a need to discover more in this area because of global environmental consciousness, competitive alertness and industry initiatives, many organizations wish for achieving sustainability in environment aspect. On the other hand, the research gap of applying KM in GSD industry in order to assist CoP in managing their knowledge lead to our future work of developing a model of GSD which involving KM process on a system to ensure members of CoP in software development environment able to manage their knowledge, promote best practices and sustain the best practices of GSD to future generation.

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## Appendix: Summary of Articles that are Included in GSD Literature Review

| Author | Year | Objective | Result and Conclusion |
|---|---|---|---|
| Albertao, Xiao, Tian, Lu, Zhang and Liu [49] | 2010 | To introduce software engineering metrics that can be used to assess economic, social and environmental sustainability of software projects. | The researchers presented well-known existing software measurements and practices in this paper. |
| Dick and Naumann [14] | 2010 | To introduce model that can enhance common software development processes in sustainable software product design. | The researchers integrated Open Unified Process (OpenUP) and Scrum, which followed agile software development methodology, to the sustainability aspects of software development. |
| Capra, Francalanci and Slaughter [15] | 2011 | To study effects on energy efficiency of abstraction layers and application development environment for | The researchers proved that different designs of software functional applications could cause different significant effect on energy efficiency. Result of their research showed |

| Author | Year | Objective | Result and Conclusion |
|---|---|---|---|
| | | software application. | that text and image editing and gaming applications had the least energy efficiency because of their intense use of processor. |
| Johann, Dick, Kern and Naumann [10] | 2011 | To introduce a model of green and sustainable software which faces the challenges of decrease in power consumption by ICT itself and use of ICT to contribute to sustainable software development. | The researchers concluded that among phases of lifecycle for software product, usage phase had the highest impacts on sustainability. Hence, a knowledge base with the objective to provide best practices, suggestions, guidelines, recommendations was needed. |
| Naumann, Dick, Kern and Johann [11] | 2011 | To structure concepts, strategies, processes and activities of Green IT, especially green and sustainable software. | The researchers concluded that software was not just a product that only made up by software artifacts, but there were still many other products and services were involved in the lifecycle of software. All of them had many influences on sustainable development. Hence, model proposed by the researchers could cover all these influences. |
| Shenoy and Eeratta [16] | 2011 | To examine changes in existing software development lifecycle and propose suitable steps to help organizations in heading to greener and sustainable software development. | The researchers developed a GSD Model that suggested various important practices in individual phases of software development life cycle that able to help in developing software program in a more environmental friendly path. |
| Steigerwald and Agrawal [57] | 2011 | To explain consideration and methodologies of software design in order to increase software energy efficiency. | The researchers concluded that in the future, energy efficiency would be extremely important for computing industry and software behavior had a crucial influence on the battery life and platform energy consumption. |
| Fakhar, Javed, Rasool, Malik and | 2012 | To identify energy conservation measures for software and to utilize at | The researchers concluded that proposed green compiler showed a performance of conserving energy clock cycle increased to |

| Author | Year | Objective | Result and Conclusion |
|---|---|---|---|
| Zulfiqar [58] | | scheduler and compiler. | 40%. |
| Fang, Liu, Yang and Liu [59] | 2012 | To introduce evolution concentrating on sustainability for Internetware software. | The researchers concluded that proposed solution of integrating sensors and event-driven transformation mechanism into Internetware software able to address the sustainability issues. |
| Johann, Dick, Naumann and Kern [50] | 2012 | To present metrics to measure software and method to apply in software engineering process. | Result of the experiments showed that an algorithm with better performance and higher asymptotic run time also had greater energy efficiency. On the other hand, energy efficiency would become lower if demand for fast response were higher. |
| Lami, Fabbrini and Fusani [45] | 2012 | To integrate greenness culture in developing software by referring to popular standards in evaluating the process capability and sustainability. | The researchers introduced a process model that enabled to be assessed in terms of process capability which sustainability issues were also injected into the processes. |
| Penzenstadler [51] | 2012 | To contribute description about aspects of software engineering sustainability. | The researcher explained how could establish sustainability through requirements engineering and quality assurance. |
| Schien, Shabajee, Wood, Yearworth and Preist [46] | 2012 | To study challenges of applying Life Cycle Assessment as a tool to improve power efficiency of digital news media products. | The researchers discovered one of the important challenges of applying LCA was about lack of transparency in environment effects in the product system. |
| Siebra, Costa, Miranda, Silva and Santos [52] | 2012 | To explore software methods in order to find out power-efficient mobile techniques. | Result showed that during idle mode, data transfer of Wi-Fi and eBook could save more energy when CPU frequency was arranged to 200 MHz. Voice call could have the best power performance when the frequency was configured to 1200 MHz. Data transfer of 3G could save more energy when in frequency of 1000 MHz. The researchers concluded that |

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| Author | Year | Objective | Result and Conclusion |
|---|---|---|---|
| | | | CPU frequency was a suitable direction to be explored. |
| Afzal, Saleem, Jan and Ahmad [53] | 2013 | To highlight various approaches and guidelines for energy efficient software development throughout the whole life cycle. | The researchers concluded that the proposed framework which combined cloud structure with green computing could develop more sustainable software. |
| Bokhoven and Bloem [54] | 2013 | To test in a real environment about how the monitoring of energy usage by software on servers. | The result showed that for an idle server, software only consumed 15% of the overall power consumption. On the other hand, for server that actually engaged in a useful process, software consumed around 72% of total power consumption. |
| Bozzelli, Gu and Lago [55] | 2013 | To categorize green software metrics that present in software engineering literature in terms of context, type and evaluation methods. | The researchers found out that most of the previous researchers were focusing on energy saving and efficiency area. Contribution of this paper able to provide future researchers to select the right set of metrics that suitable for their use. |
| Chauhan and Saxena [56] | 2013 | To recognize energy-saving opportunities in standard software development life cycle in helping to develop environment-friendly software for cloud setup. | The researchers proposed a set of guidelines that should be included in the process of developing software. |
| Dick, Drangmeister, Kern and Nauman n [60] | 2013 | To propose a model that integrates agile methods with green software engineering processes. | The researchers proposed integration with Scrum, which followed agile software development methodology, to be applied to the software development process, to achieve green and sustainable objective. |
| Erdelyi [13] | 2013 | To study activities of software development | The researchers concluded that computational efficiency and data efficiency |

| Author | Year | Objective | Result and Conclusion |
|---|---|---|---|
| | | life cycle and how they contribute to environmental sustainability. | were needed to be achieved in order to reach energy efficiency. |
| Grosskop and Visser [61] | 2013 | To recognize energy-efficient optimizations in software applicns. | The researchers discovered that most of the stakeholders had only a low degree of awareness about software sustainability was also a significant part in Green IT. Through the scenario-based Green Software Scan, the researchers concluded that in order to optimize the energy efficiency of software development, active communication and collaboration between development team and operating employees were a strong success factor because able to collect information from different parties and fully understand the requirement and architecture in the early stage of the entire lifecycle. Moreover, the researchers concluded that changes in architecture, design and deployment of software tend to have bigger impact in energy optimizations compared low-level algorithmic optimizations method. |
| Karunakaran and Rao [62] | 2013 | To achieve ideal resource configuration for software development process and minimize carbon footprint. | The researchers concluded that in order to develop software with lower cost and lesser carbon footprint, medium skilled developers were the best suited. |
| Kern, Dick, Naumann, Guldner and Johann [63] | 2013 | To explain a model for measuring energy efficiency of software. | SUT supporting HTML-Cache able to save around 8.6% of electrical energy compared to SUT without HTML-Cache. Besides, around 19% of reserve capacity could be generated. |
| Kocak [64] | 2013 | To discover trade-off between software sustainability | Result of the research showed that environmental sustainability was the most preferred to achieve the |

| Author | Year | Objective | Result and Conclusion |
|---|---|---|---|
| | | and quality requirements. | goal of developing sustainable and green software. Criterion of power consumption was the most significant concern in environmental sustainability matter, followed by carbon dioxide emission issue. On the other hand, from software quality perspective, criterion of efficiency of the developed software had the highest priority, followed by reliability of the software. |
| Kocak, Miranskyy, Alptekin, Bener and Cialini [48] | 2013 | To study trade-off between software functionality and power consumption of software. | Configuration with compression of data caused 97% performance improvement but 29% increase in power consumption compared with reference configuration. However, power consumption per unit of work could be decreased by 34% because of the increased query throughput. The researchers concluded that legacy system modernization with the increase in system functionality would lead to consumption per unit of time increased and consumption per unit of work decreased. There was a mixed influence on power consumption. |
| Mahmoud and Ahmad [65] | 2013 | To design a model that covers all aspects of green computing in terms of software. | The researchers concluded that the two-level model able to help in developing green and sustainable software product. |
| Moshnyaga [66] [67] | 2013 | To analyze total energy consumption and green-house gas emissions of software production, delivery and use. | Results showed that production energy dominated total lifecycle energy if number of software users was little. On the other hand, most of lifecycle energy was consumed at use phase if software became popular among users or number of software copies was large. |
| Moshnyaga [68] | 2013 | To examine power consumption of | Result of the research showed that power consumed at production phase |
| | | production, delivery and use of application for mobile devices. | would be a dominant cause in the total energy of lifecycle if the application size increased. Most of energy of lifecycle would be consumed due to updates if the applications were wisely used. Besides, result proved that low energy consumption, low upload and download size of Mail K9 caused the application was capable of being labeled as green application of mobile devices. |
| Penzenstadler [69] | 2013 | To provide software developers and engineers about how sustainability can be integrated into daily practices. | The researchers presented ways to improve sustainability for software engineering and in software engineering. |
| Samuel and Kovalan [70] | 2013 | To evaluate characteristic of mainstream programming paradigms about which one will use lesser resources from mobile devices. | The researchers concluded that minimization in using object-oriented features, for example: inheritance, concatenated strings thread synchronization, recursion, and declared global variables, able to avoid stack overflow and memory leak. Besides, several functional programming characteristics were more suitable for green mobile computing, for example: parametric polymorphism, higher order functions, list comprehension principles and referential transparency. |
| Scanniello, Erra, Caggianese and Gravino [47] | 2013 | To provide existing software system a better eco-sustainable lease of life with migration strategy. | The results showed that execution time and energy consumption of migrated system were lesser than the original one. However, execution time and energy-saving were not directly related. |
| Kern, Dick, Naumann and Hiller [71] | 2014 | To introduce carbon footprint calculation method for software product life cycle. | The researchers concluded that the proposed methods helped software developers to make software greener without changing the software engineering methods in general. There were many aspects needed to be |

| Author | Year | Objective | Result and Conclusion |
|---|---|---|---|
| | | | taken into account in the calculation, especially commuting was one of the important aspect. |
| Kocak, Apltekin and Bener [72] | 2014 | To investigate relationships between quality and environmental attributes. | Between the two environmental criteria, criterion of resource usage had a larger impact on GSD compared to criterion energy impact. Among the four quality criteria, reliability had the highest impact. The proposed ANP framework proposed by the researchers able to support software developers about the requirements' priorities. |
| Penzenstadler, Raturi, Richardson, Femmer, Calero and Franch [73] | 2014 | To develop systematic mapping study on software engineering for sustainability (SE4S) from year 2012. | The study showed that the majority of publications were about software design, model and methods, engineering management, requirements, quality, and process. Popular topics were power efficiency, future of society and life cycle assessment. |
| Rossi, Xavier, Conte, Ferreto and De Rose [74] | 2014 | To answer about use of multi-core processors in an energetically efficient way. | The result proved that it was true about in two-core processor, energy saving could be achieved if all threads migrated to one processing unit and turned off another unit. Besides, if all the threads were in a fair distribution among all available cores, then energy saving could also be achieved. However, use of hyper-threading increased, energy consumption would also be increased. |
| Thiry, Frez and Zoucas [75] | 2014 | To present a reference model for GSD. | The researchers concluded that the proposed GreenRM model united concepts of GSD with ISO/IEC 14001 environmental requirements, which could be a guide for application of Green IT practices. |
| Naumann, Kern, Dick and Johann [76] | 2015 | To develop the software itself and also the software development process become more sustainable. | The model developed by researchers was able to include sustainability qualification process, which did not include in previous sustainability engineering process that introduced by other researchers. Besides, social aspect should be also included in sustainable software engineering process. |

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