Synchronisation for Dynamic Load Balancing of Decentralised Conservative Distributed Simulation

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ABSTRACT
Synchronisation mechanisms are essential in distributed simulation. Some systems rely on central units to control the simulation but central units are known to be bottlenecks [10]. If we want to avoid using a central unit to optimise the simulation speed, we lose the capacity to act on the simulation at a global scale. Being able to act on the entire simulation is an important feature which allows to dynamically load-balance a distributed simulation. While some local partitioning algorithms exist [12], their lack of global view reduces their efficiency. Running a global partitioning algorithm without central unit requires a synchronisation of all logical processes (LPs) at the same step. We introduce in this paper two algorithms allowing to synchronise logical processes in a distributed simulation without any central unit. The first algorithm requires the knowledge of some topological properties of the network while the second algorithm works without any requirement. The algorithms are detailed and compared against each other. An evaluation shows the benefits of using a global dynamic load-balancing for distributed simulations.

Keywords
Dynamic load-balancing; Synchronisation; Distributed simulation

1. INTRODUCTION

Distributed simulation is an important tool in many scientific fields. It has been designed to answer to problems such as processing power requirement, volatility or stability. However, using distributed systems instead of a single processor (running a non-distributed simulation) leads to issues such as dividing and balancing efficiently the load, minimising the communication cost and synchronising LPs. A lot of work has been done in this area. For instance, [16, 32, 34] present algorithms - respectively called METIS, QuadTree and SParTSim - used to partition a simulated environment. QuadTree partitions the environment into smaller regions according to spatial information. METIS tries to simplify a weighted graph before dividing it, then it projects the partitions back on the original graph. SParTSim uses traffic characteristics, such as the importance of the roads, the number of vehicles, the number of neighbours per region, to partition road networks. Various work have tackled the problem of maximising the efficiency of the communication in general distributed systems. Message Passing Interface [31] is one of the most known communication system while some work try to develop their own library [22], especially in graph processing [7, 24, 21]. Synchronisation between the different parts of a distributed system is critical and synchronisation mechanisms can be classified in two categories [11, 20, 3, 19]: conservative or optimistic. The former does not allow any causality violations, i.e., any two events have to be processed in the same order in any LP where they are present, while the latter allows LPs to process events even if they may raise contradictions and need to be roll-backed. There is no strict consensus on which synchronisation mechanism is the best.

Once these three characteristics (workload partitioning among the LPs, communication, synchronisation) are set for a distributed simulation, there is still one element that can hamper the efficiency of the system: the system evolves and the load apply to each LP may vary. In that case, some LPs will have more work to compute while the others will be waiting, and the overall simulation will be slower. It is generally accepted that dynamic load-balancing is necessary for distributed simulations [12, 9, 37]. However, those work focus on local dynamic load-balancing as none of them uses a central unit to monitor the distributed simulation. While they offer fair results, they cannot compete with global load-balancing due to their lack of global information. The problem now is that centralised distributed simulations are not always a good solution - as they generate single points of failure for instance.

In this paper we address the question of the feasibility of overall synchronisation for dynamic load balancing of decentralised conservative distributed simulations. In short, (i) LPs can process a step at a time, and wait for their neighbours to finish their steps before processing the next one (conservative); (ii) there is no central entity to orchestrate/monitor the simulation; and (iii) the load in the system tend to be imbalanced after some time. This scenario is common in distributed simulations [37] and to the best of our knowledge there is no adequate solution that addresses it. We propose two novel algorithms that allow to provide an
overall synchronisation\footnote{In this paper we use ‘overall synchronisation’ or ‘synchronisation’ for the same process of stopping all LPs at the same step.} of the system at a particular step, i.e., stop all the LPs at the same step, so that some global process can happen (repartitioning to dynamically load balance the system in our case): TaSyn and GenSyn. TaSyn requires some topological information on the distributed simulation, such as eccentricity of each node, while GenSyn does not require any additional information and only floods the graph of LPs to figure out the best step to stop the simulation at. We show also in this paper that dynamic load-balancing mechanisms (either using TaSyn of GenSyn) can improve the processing time of a distributed simulation. In particular we find that the time saved using dynamic load-balancing, depending on the sensitivity of the algorithms to load imbalance in the system, is comprised between 7.4% and 15.1% (over 200 steps of simulation).

In the remainder of the paper we explain with more details the requirements of a global synchronisation mechanism (Section 2 and in general what distributed simulation are (Section 3). Section 4 details the two algorithms and compares them while Section 5 shows the impact of a dynamic global load-balancing on a distributed simulation. Finally, Section 6 concludes this paper and presents some future work.

2. MOTIVATION

Several approaches to synchronise distributed systems exist depending on the scale (LANs, WANs) or the kind of system (peer-to-peer, data-centre, clouds computing)\footnote{extension} [30, 25, 1]. However, those mechanisms are complex and deal with issues such as time-shift or fault-tolerance. While those issues are real at a physical level, they are not relevant in time-discrete distributed simulation, where time is measured logically by the number of steps executed by a LP. We can classify distributed simulations in two categories: distributed simulations with a central unit and distributed simulations where LPs share information locally. At the end of each step, LPs will report their activities to the central unit which will take decisions for the next step for the whole simulation. In this case, synchronising and stopping every LPs at the same step seems straightforward as the central unit knows the state of every LPs and can easily find the first step to stop at. However, distributed simulations with central unit are not always a good solution as the central unit can be a bottleneck. When information are shared locally, each LP communicates directly with its neighbours and LPs do not have a full knowledge of the network.

As workload is transferred through the distributed simulation, some LPs might receive more load than others and, therefore, take more time to complete their work. Each LP depending on the outputs of those slow ones will in turn be slowed down and eventually the whole simulation slows down. In order to prevent this issue, the simulation must find a way to globally balance the load over the LPs. However, without a central entity, this operation can be complex. First of all, a LP has to understand that the distributed simulation could have faster results. Different solutions can be imagined to evaluate a slowdown. The first way can be through synchronisation messages: each time the LPs synchronised, they send a message with their actual load and compare the value with their neighbours or with the average load. It would be possible for a LP to periodically broadcast a message in order to share information about its load. However, if we want this solution to be more efficient than local dynamic load-balancing, we have to broadcast the message far away from its origin which will considerably increase the communication on the network. An ideal solution would be for a LP to be able to evaluate itself without sharing information with the rest of the simulation. While a LP alone cannot evaluate how much slower it is compared to its neighbour, it is possible for a faster LP to evaluate how much faster it is. After a step - or few steps with optimistic synchronisation mechanism - a LP requires to synchronise with its neighbours. Measuring the time between the end of its step and the last neighbour synchronising would give an idea about how faster the LP is. An evaluation can be conducted during the simulation without perturbing the processing just by measuring the slowest response time and compare it with a threshold. If during a couple of consecutive synchronisations, the latency is higher than usual, the problem might come from an unbalanced state of the simulation. Thus, the LP detecting the unusual latency is able to trigger an overall synchronisation.

3. RELATED WORK

Distributed simulation is the representation of the evolution of a system using multiple LPs working together. They can be used to simulate work such as adaptive mesh refinement\footnote{extension} [18], car crashes [29], behaviour simulation [5, 8], graph functions [6] and others. To respond to those requirements, distributed simulations can take a lot of forms: continuous or discrete time/space, time-step or event-driven, local or global communication (through a central unit). However, they all share the same basic requirements: a partitioning algorithm to distribute as evenly as possible the load among the LPs, a communication mechanism to allow LPs to exchange information and a synchronisation mechanism to allow LPs to organise themselves when needed.

3.1 Partitioning Algorithms

For the distributed simulation to be efficient, it is important to distribute the load as fairly as possible between each LP. As shown section 5, disparity among the load can have important consequences on the overall simulation time. A lot of research has been conducted to address this problem, leading to numerous algorithms including uniform and nonuniform space partitioning [33, 23, 2, 32], graph partitioning [16, 17] (some designed for specific tasks including road traffic partitioning [34, 36]), car crashes analysis [29] and others.

3.2 Communication Mechanism

The aim of the communication mechanism is to ensure that LPs share information throughout the simulation. It is a critical element as the very idea of LPs working together is based on their capacity to communicate. If the communication library is not efficient enough, it can lead to an important slow-down of the overall simulation. The most used communication library is MPI [31] as it is well-known to be efficient, simple to use and portable. Extensions of MPI have been developed to improve its efficiency. For instance, MPICH-G2 [15] has been designed to handle heterogeneous communication environments where commu-
通信延迟是不均匀的。为了最小化通信的影响，有些工作尝试通过负载平衡通信，而在分割环境中部分地 \cite{34, 27}。

### 3.3 Synchronisation Mechanism

同步机制也需要用于一个有效的分布式模拟。它保证了在正确的顺序处理消息，其保证了顺序的正确。这种法律被称为本地因果约束。Fujimoto \cite{11} 将同步机制分为两类：保守同步化和乐观同步化，依赖于发布的分布式模拟。因此，没有共识似乎已经形成了。在这种情况下，我们可以通过对方或另一个。

#### 3.3.1 Conservative Synchronisation

保守同步化是设计得这样，当本地因果约束不能被违反。例如，保守的时间步进式分布式模拟在每个模拟步骤之后允许同步。当，而且只有当，一个LP确信没有消息将到达一个较小的时戳时，它将执行下一步。在某种方式下，乐观的同步化是可能的。通过发送请求到所有的LP，可以解析出一个图的信息，以便找到一个可能的步骤。

#### 3.3.2 Optimistic Synchronisation

另一方面，乐观的同步化允许LPs在不违反本地因果约束的情况下，可以缩小每几步中的步骤。因此，它在可以收到一个消息，该消息在有更小的时戳时出现。在上一步结束时，LPs可能需要在步骤t+1前接收该消息，并处理该消息。然而，回退可能会有很大的成本，因为该模拟需要重新加载其前一个状态并重新启动步骤。

### 4. SYNCHRONISATION

同步化模拟是一个至关重要的任务，甚至是一个用户的行动，可能影响整个分布式的模拟。例如，在分布式的模拟中，保持一个良好的负载平衡之间的LPs是重要的，因为结果的同步化导致了在模拟中保持平衡。当它在步骤中，可能会有预测到的改变，并因此计划改变。因此，LPs之间的数据交换可以发生。例如，当LPs与邻居通信时，可能会发送请求。这些请求可以发送到所有LPs，以达到同步。然而，必须最小化通信的延迟变化，这些变化要求动态的异步化。负载平衡可以在本地由交换完成，例如，通过与邻居的通信。然而，这也意味着在步进中可能会有耗时的通信。

#### 4.1 Graph Theory and Distributed Simulation

它被广泛接受，作为分布式的模拟，特别是分布式的系统 - 是由LPs组成分布式系统，结构可以被比较于图，其中进程在通信和计算之间可能具有相等的边。图理论的概念可以扩展到图理论，例如：

- **Eccentricity**
  - 一个图的中心是最大距离，其中有一个顶点和另一个图的任意一个顶点。延展，一个图的LP将是最大距离，其中有一个LP和另一个LP。例如，在一个LP，最大的图理论的图是3，因为它是图的直径。在相同的情况下，图理论的图是局部的图，具有等同于边缘的值。2，因此，图的图是2。

- **Peripheral vertices**
  - 边缘的LPs在图的边缘，称为图的边缘，该值称为边缘的等同于中心的图。在相同的方式中，中心的LPs是图的LPs，称为图的等同于边缘的等同于中心的图。在相同的方式中，中心的LPs是图的LPs，称为图的等同于边缘的等同于中心的图。

#### 4.2 TaSyn: Topologically-aware Synchronisation

TaSyn，作为一个时间步进式同步化，使用图理论的图，在一个LP上找到一个步骤，当LPs可以同步化。时间步进式分布式的模拟使用局部保守的同步化，允许小范围的时间灵活性，特别是在一个LP和它的邻居之间。例如，如果一个LP在步骤t+1，它的邻居将会收到LP的信息，要求计算步骤t，即使在n的结束时，t + 1。在t的结束时，它的邻居n。在步骤t的结束时，n将有足够的时间信息来计算步骤t + 1，即使n在步骤t + 1没有移动。通过过渡，两个LPs之间的步骤数是不同的LPs。因此，最大的步骤数是两个LPs，且具有不同的步骤数，可能相同于两个LPs。因此，最大的步骤数是两个LPs，且具有不同的步骤数，可能相同于两个LPs。
in the distributed system. If the eccentricity is known before running the distributed simulation, a LP can safely request a general stop at the following step:

\[ \text{synchroStep} = e(n_t) + s(n_t) \]  

with \( n_t \) the LP triggering TaSyn, \( e(n_t) \) the eccentricity of \( n_t \) and \( s(n_t) \) the current step of \( n_t \). If we know the topology of the distributed simulation, algorithms such as Johnson’s algorithm [14] offer the possibility to process the eccentricity of each node in the graph.

\[ \text{Algorithm 1: TriggerLP for TaSyn} \]

1. \( \text{if } \text{triggered is false } \& \text{ synchronising is false then} \)
2. \( \text{synchronising } \leftarrow \text{true; } \)
3. \( \text{synchroStep } \leftarrow \text{eccentricity } + \text{currentStep; } \)
4. \( \text{sendToAll("SYN " + synchroStep); } \)
5. \( \text{// The LP can continue until reaching synchroStep} \)

\[ \text{Algorithm 2: Regular LP for TaSyn} \]

1. \( \text{parents } \leftarrow \text{new array; } \)
2. \( \text{foreach msg in msgBox do} \)
3. \( \text{if msg.startWith("SYN") is true } \& \text{ synchronising is false then} \)
4. \( \text{synchronising } \leftarrow \text{true; } \)
5. \( \text{tempStep } \leftarrow \text{msg.split("")}[1]; \)
6. \( \text{if tempStep < synchroStep then} \)
7. \( \text{synchroStep } \leftarrow \text{tempStep; } \)
8. \( \text{parents.add(msg.sender); } \)
9. \( \text{foreach n in neighbours do} \)
10. \( \text{if n is not in parents then} \)
11. \( \text{n.send("SYN " + synchroStep); } \)
12. \( \text{// The LP can continue until reaching synchroStep} \)

An important question to ask at this stage is: what happens if two LPs trigger the algorithm? If two LPs are at the same step and have the same eccentricity, they will send the same message. If a LP receives two messages at the same time, it will just assume that the two LPs are its parents. If one message comes later, it will just be discarded. When the value carried by the messages is not the same, the LP will select the lowest value as by definition, both values correspond to a safe step to stop at. Figure 1 presents a case of collision between LP \( F \) which has an eccentricity of 3 and is at the step 9 and LP \( H \) which has an eccentricity of 4 and is at step 10.

TaSyn is simple and straightforward but does not compute the first step where it is possible to stop because the triggering LP does not know at which step the other LPs are. It only knows that they are within the boundary of the constraint.

4.3 GenSyn: General Synchronisation

When it becomes important to stop the distributed simulation as soon as possible, GenSyn, which stands for General

\[ \text{Propagation (PRP). The first phase consists in propagating a message through the distributed simulation to find the LP with the highest step. Each LP receiving one or more messages from its neighbours will compare its step with the step contained in each message. The LP will place the highest step in a message and forward it to all its remaining neighbours while the sender(s) id(s) will be stored. If the LP receives a message after it has propagated to its neighbours, the message is discarded. Figure 2(a) presents the propagation of the message if the LP \( F \) triggers GenSyn.} \]

\[ \text{Answer (ANS). If after removing its parents, a LP has no other neighbour to propagate the message to, the second phase starts and the LP sends back to its parents an answering message containing the highest step stored. Each LP waits for an answer from all its children before forwarding back its own answer. Figure 2(b) shows how the answer will be sent back to the root LP \( F \).} \]

\[ \text{Confirmation (CNF). Once the triggering LP has received answers from all its neighbours, it sends a confirmation message with the highest step of the distributed simulation. Each neighbour stores the step contained in the confirmation message and continues its work until it reaches this step. Figure 2(c) presents the propagation of the confirmation message.} \]

\[ \text{Algorithm 3: Leader LP for GenSyn} \]

1. \( \text{if triggered is true } \& \text{ synchronising is false then} \)
2. \( \text{synchronising } \leftarrow \text{true; } \)
3. \( \text{leader } \leftarrow \text{false; } \)
4. \( \text{sendToAll("PRP " + currentStep+" " + id); } \)

In case of collisions, the LP arbitrary selects the smaller id between the LPs triggering the algorithm.

4.4 Efficiency of GenSyn and TaSyn

Information about the eccentricity of each LP used by TaSyn makes it far less complex than GenSyn. However, despite the fact that this information is not always available,
TaSyn’s simplicity does not make it more efficient in every case. To compare the, we consider that each LP has to wait until the global synchronisation is finished to process the remaining steps. In other words, the communication phase and the processing phase will be executed sequentially - in practice, intermediate LPs can start processing steps if they know they are at a lower step compared to the potential maximum (i.e., they received propagation messages with a higher step than their actual one).

To reach the furthest neighbours, TaSyn requires a number of steps equal to the eccentricity of the triggering LP. The remaining step(s) to process for a LP will be the difference between the triggering LP current step added to its eccentricity and the current step of the LP. Therefore, TaSyn communication time (CommTimeTaS) and processing time (StepTimeTaS) requirements are:

$$\text{CommTime}_{TaS} = t_u \times e(n) \quad (2)$$

$$t_u \times e(n) \leq \text{StepTime}_{TaS} \leq t_u \times (e(n) + s(n) - \min(s(n))) \quad (3)$$

As the communication phase of GenSyn consists in crossing the network 3 times, its communication phase is 3 times longer than TaSyn. The maximal number of steps required before reaching the synchronisation step is given by the difference between the highest step and the lowest step present on the simulation. From that point, GenSyn communication time (CommTimeGenS) and processing time (StepTimeGenS) requirements are defined as:

$$\text{CommTime}_{GenS} = t_u \times 3 \times e(n) \quad (4)$$

$$0 \leq \text{StepTime}_{GenS} \leq t_u \times (\max(s(n)) - \min(s(n))) \quad (5)$$

with CommTimeTaS and CommTimeGenS respectively TaSyn and GenSyn’s communication times, StepTimeTaS and StepTimeGenS respectively TaSyn and GenSyn’s processing times, $t_u$ the time required to send a message to a neighbours, $n$, the LP triggering the algorithm, $e(n)$ the eccentricity of the LP $n$, $t_s$ the time required to process a step and $s(n)$ the step of LP $n$. The minimum value for the processing time happens when the LPs are all close to be at the same step which means $\max(s(n)) - \min(s(n)) = 0$, while the maximum processing time occurs when the LPs are at completely different steps and then $\max(s(n)) - \min(s(n)) = \max(e(n))$. For the comparison, we will assume that we are in the worst case, $\max(s(n)) - \min(s(n)) = \max(e(n))$ but the process is identical for the case 1 and for the intermediate values. By adding equations 2 to 3 and equations 4 to 5, we obtain the total time required respectively by TaSyn and GenSyn. As we want to compare them according to the topology of the graph, the communication time and the processing time, we can write:

$$\text{TotalTime}_{GenS} = \text{TotalTime}_{TaS}$$

$$t_u \times 3 \times e(n) + t_u \times \max(e(n)) = t_u \times e(n) + t_s \times 2 \times e(n)$$

$$t_u \times (2 \times e(n)) = t_u \times (2 \times e(n) - \max(e(n))) \quad (6)$$

In graph theory, it is proven than radius $\leq$ diameter $\leq 2 \times radius$ [4]. As explained before, the diameter is the maximum eccentricity so $\text{dia} = \max(e(n))$ and the radius the minimum eccentricity $\text{rad} = \min(e(n))$. In the case of $\text{dia} = 2\text{rad}$, if $n$ is a pseudo-peripheral LP - $\text{rad} \leq e(n) \leq \text{dia}$ - from equation 6, the relation between the communication time and the processing time is given by:

$$t_u = \frac{t_u \times (2 \times e(n) - \text{dia})}{2 \times e(n)} \quad (7)$$

If $n$ is a central LP - $\text{rad} = e(n)$ -, as $\text{dia} = 2 \times \text{radius}$, the equation 7 can be reduced to:

$$t_u = \frac{t_u \times (\text{dia} - \text{dia})}{2 \times e(n)}$$

$$t_u = 0 \quad (8)$$

Finally, if $n$ is a peripheral LP - $\text{dia} = e(n)$ -, for the same reason, we can reduce equation 7 to:

$$t_u = \frac{t_u \times (2\text{dia} - \text{dia})}{2 \times \text{dia}}$$

$$t_u = \frac{1}{2} \times t_u \quad (9)$$

Equation 8 proves that, if the LP triggering the algorithm is a central node, TaSyn will always be faster than GenSyn.
Algorithm 4: GenSyn LP for TaSyn

```java
parents ← new array;
foreach msg in msgBox do
  tempRootId ← msg.split(" ")[2];
  if rootId == null then
    rootId ← tempRootId;
  else if tempRootId < rootId then
    rootId ← tempRootId; nbPrp ← 0; nbAns ← 0;
foreach msg in msgBox do
  if msg.startWith("PRP") is true then
    nbPrp ← nbPrp + 1;
    tempStep ← msg.split(" ")[1];
    triggered ← true;
    parents.add(msg.sender);
    if synchronising is true then
      synchronising ← true;
      currentMaxStep ← step;
    if tempStep > currentMaxStep then
      currentMaxStep ← tempStep;
    if nbPrp == neighbours.size() then
      foreach p ∈ parents do
        if n ∈ parents then
          n.send("ANS "+currentMaxStep);
          parents.clear();
      else
        prpToSend ← true;
      else if msg.startWith("ANS") is true then
        nbAns ← nbAns + 1;
        currentStepMax ← msg.split(" ")[1];
        if leader is true & nbAns == neighbours.size() then
          stoppingStep = currentStepMax;
          sendToAll("CNF "+stoppingStep);
        else if nbPrp+nbAns == neighbours.size() then
          foreach p ∈ parents do
            p.send("ANS "+currentMaxStep);
            parents.clear();
        else if msg.startWith("CNF") is true & confirmation is false then
          confirmed ← true;
          stoppingStep ← msg.split(" ")[1];
          parents.add(msg.sender);
          foreach n ∈ neighbours do
            if n is not ∈ parents then
              n.send("CNF "+stoppingStep);
        if prpToSend is true then
          foreach n ∈ neighbours do
            if n is not ∈ parents then
              n.send("PRP "+currentMaxStep);
```

However, if the triggering LP is a peripheral node, GenSyn will be faster than TaSyn if the communication time is less than twice the processing time. Similarly, if the LP trigger is a pseudo-peripheral node, the relation between the communication time and the processing time is given by the equation 7.

Using the same way, if we are in the case of $\text{dia} = \text{rad}$, all LPs have the same status and the equation resulting is:

$$t_u = t_s$$

Which means that no matter which LP triggers the algorithm, GenSyn will outperform TaSyn if the communication time is smaller than the processing time.

If we are in the case where $\text{rad} < \text{dia} < 2\text{rad}$, by declaring $\text{dia} = 2\text{rad} - x$ with $0 < x < \text{rad}$, we obtain the following equations:

$$t_u = t_s \times x \over 2\text{rad}$$

$$t_u = {t_s \over \text{dia}}$$

$$t_u = t_s \times \text{dia} \over 2 \times r(n_t)$$

t for a triggering LP respectively a central node 11, a peripheral node 12 and a pseudo-peripheral node 13.

This comparison shows that neither TaSyn nor GenSyn outperforms the other. Therefore, the user can select which algorithm is more suitable for its distributed simulation depending on the following features: communication time, processing time, network topology and the position of the node if known.

5. EXPERIMENTATION

To test their efficiency, we implement our algorithms into the simulator of distributed system PeerSim [26] and simulate the behaviour of the distributed simulation.

5.1 PeerSim

PeerSim has been developed to simulate and test distributed (peer-to-peer) systems. Its main features are its scalability, which allows it to run algorithms on hundreds of thousands of nodes quickly, its modularity as all the components are configurable and its graph abstraction, useful to import networks as graphs and use topological information. PeerSim also implements two types of simulations, event-based and cycle-based. We choose to implement our algorithms with the cycle-based simulation as we are studying time-stepped simulations. For each PeerSim cycle, LPs are randomly selected and executed one after another.

5.2 Scenario

We measure the impact of dynamic load-balancing by using a distributed simulation implementing our algorithms against a reference distributed simulation. Our distributed simulation will be able to perform a global dynamic load-balancing but not the reference. We simulate a 200 steps-long stepped-based distributed simulation using PeerSim. Each Peersim cycle, the LPs increase a value until they reach their maximum load. It is a simple task representing the LPs doing their part of the simulation. When a LP reaches its maximum load, it sends to its neighbours an
end-of-step message and waits until all its neighbours send back the same message. Once the end-of-step messages are gathered, the LP calls a method to increase or decrease its maximum load of 1%, depending on a random value. This phase represents the fact that a distributed simulation seldom stays at the optimal state of a perfect load-balance. Then, the LPs will proceed to the next step with more load, or less load, than its neighbours. It is very likely that, after a while, some LPs will have a lot more, or a lot less, work than others and will slow down the simulation, or have to wait a long time. From this point, the simulations using GenSyn and TaSyn will try to synchronise the distributed simulation in order to perform a dynamic partitioning which will bring-back the load-balanced state. On the other side, the reference simulation will have to continue with its unbalanced state. It will allow us to compare the effect of the dynamic-load balancing against its absence and measure its impact in term of simulation time.

In order to trigger the global synchronisation algorithms, and therefore the dynamic partitioning, a LP will compare the time it requires to simulate a step against the time it has to wait its neighbours. We will set 4 different thresholds in order to compare their impact. We have chosen as thresholds:

\[
\text{StepTime} = \{1/2, 1/4, 1/8, 1/16\} \quad \text{WaitingTime}
\]

For the scenario of our algorithm, we did not implement any specific partitioning algorithm to run when the LPs are synchronised which could, in some cases, take a certain time. Following the same idea, our LPs communicate by shared memories which cannot be compared, in term of time, with messages sent in the network. However, we will present our results being aware of those two missing constraints.

5.3 Metrics

The first observation we expect is a global impact such as represented by the Figure 3. Optimal time means the time to process the simulation if the system is perfectly load-balanced. As the simulation is losing its load-balanced state, the time want measure the average time required by all the LPs to move to the next step, which means both the processing-time and the waiting-time. This measure will show us the impact of the load-balancing on each step of the simulation and on the overall simulation. The time gained over the whole simulation will be obtained from:

\[
\text{TotalTimeGained} = \frac{\sum_{i=0}^{n} \sum_{j=0}^{m} (s_j)}{m} - \frac{\sum_{i=0}^{n} \sum_{j=0}^{m} (r_j)}{m}
\]

where \(n\) is the number of steps, \(m\) the number of LPs, \(s_i \in S\) the values of the simulation without the synchronisation and \(r_i \in R\) the values of the simulation including a synchronisation. The different measurements according to each threshold will allow us to evaluate the efficiency of a load-balancing methods regarding the unbalanced state. In order to obtain the efficiency per synchronisation, we will divide the percentage of time gained by the number of synchronisations. The efficiency of the synchronisation will allow us to discuss over the time we can spend running a real partitioning algorithm. Lastly, we will measure and compare the reduction of waiting time obtained thanks to the load-balancing. We will trigger our algorithms using the four different thresholds introduced above.

5.4 Results

Our first concern was to observe the behaviour expected from Figure 3 and all the measurements confirm our expectations. Figure 4(a) presents this behaviour around step 80 while figure 4(b) presents it three times around steps 50, 115 and 165. Both figure 4(c) and (d) show this behaviour several times along the simulation. These are a series a great figures that show exactly what we expected: the system diverge to a imbalanced state and both GenSyn and TaSyn allows it to come back to a balanced state, more or less quickly depending on the sensitivity of the algorithms (i.e., threshold).

Figures 5(a-d) present the overall time required to execute the 200 steps of the simulation. As expected, a divergence is observed on all figures. Moreover, while the sensitivity of the synchronisation trigger increases, the gap between the reference simulation and the two other keeps increasing. It
Figure 4: Evolution of the time required per step over the simulation. The lower the better.

Figure 5: Simulation time for the whole simulation. The lower the better.
results from the number of synchronisations as the more the simulation synchronises, the more the load-balance will be brought back closer to its optimal state. We can note as well that the curves are linear which lead to think that the longer the simulation will be, the more time will be gained. We find that the gain is very similar for TaSyn and GenSyn: from 7.4% for a TaSyn and threshold of 1/2 (7.6% for GenSyn), to 15.1% for GenSyn and a threshold of 1/16 (14.9% for TaSyn) - 13.5% for GenSyn and a threshold of 1/4 (13.2% for TaSyn), 14.9% for GenSyn and a threshold of 1/8 (14.5% for TaSyn). This is a very good result as processing time is often the critical metric for distributed simulations.

Figure 6 presents the time lost in average by each LP at each step (we compare to the average time for a simulation without imbalance). At the optimal state, each LP will finish its step at the same time and the waiting time will be limited to the time required to exchange end-of-step messages. While the reference simulation misuses between 0.9ms and 1ms per step, the average waiting-time decreases as we increase the sensitivity of the trigger. If the synchronisation is triggered more often, the simulation will be brought closer to the optimal load-balance state more often.

Efficiency of the synchronisation is an important measure. As we did not implement any time-consuming load-balancing algorithm - what they usually are [13] - we need a way to evaluate how many times we have at our disposition to add the time required for the load balancing and the exchange of synchronisation messages. Figure 7 presents the efficiency of a synchronisation in our different test-cases. On a simulation of 200 steps, the efficiency of a synchronisation would be close to 7% for both TaSyn and GenSyn with a trigger set at 1/2. However, the efficiency decreases rapidly at 3.5% for GenSyn and 2.8% for TaSyn with a trigger set at 1/4. It seems to stabilise around 2% and 1.8% for a trigger respectively at 1/8 and 1/16. In a real situation, we would also have to take care of the efficiency of the load-balancing algorithm used to determine how much time we can allow to it and how many times we can run it during the distributed simulation. However, those results are the proof that there is certainly room for improvement.

Figure 6: Average waiting time of each case over the four thresholds.

Figure 7: Efficiency of a dynamic partitioning according to the threshold of the trigger.

6. CONCLUSION

This paper introduces two algorithms TaSyn and GenSyn which are able to synchronise globally a time-stepped conservative distributed simulation. This global synchronisation makes global actions possible, such as a global-scale load-balancing in an environment where information are only shared locally or unpredictable requirement to dump the memory because of imminent failure. GenSyn and TaSyn complexities have been compared and we have proven that their efficiency depends on the structure of the distributed simulation as well as the communication latency and the time required to perform a step. We have also compared, by simulation through PeerSim, a distributed simulation able to perform a global dynamic load-balancing against a distributed simulation which cannot load-balance itself. The results show that dynamically load-balancing a distributed simulation is an important operation which offers great improvements on the simulation time.

As future work we would like to compare our fully decentralised approach and high level architectures (HLA) and investigate whether TaSyn/GenSyn can still be applied (e.g., replace the synchronisation management offered by RTI). We are also interested in implementing our algorithms in distributed simulations (e.g., [5]) to evaluate the overhead of synchronisation and load-balancing on a real system. Eventually, our main target now is to compare global and local load-balancing on the system.

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8. REFERENCES


