A Mathematical Formulation for Estimating Age Levels in the Carolina Curriculum

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Abstract: The study of medical protocols for monitoring and analyzing the development of children with disabilities is a fundamental research area. A well established curriculum-based assessment is the *Carolina Curriculum for Infants and Toddlers with Special Needs* (CCITSN) together with the *Carolina Curriculum for Preschoolers with Special Needs* (CCPSN). These are suitable curriculums for early intervention programs, where sequenced item data collection and analysis are used to monitor incremental changes of the program and to recognize the areas of relative strength and weakness in an individual infant, or child, with mild and moderate disabilities. In many recent papers, Cuomo, et al. introduced the client-server software *C@rolin@* to carry out all features of CCITSN, afterwards a Social Framework and an App (CarolApp). Despite of all these technological advantages, the software uses mathematical formulas that do not fully satisfy operators and do not help them to correctly establish useful parameters. We address this problem by developing a more formalized mathematical model in the determination of age levels that can be successfully used in the Carolina software.

1 INTRODUCTION

The study of medical protocols for monitoring and analyzing the development of children with disabilities is a very spread out research area (cf. (Chapman and Hesketh, 2000)). Many studies in this field are based on *means-end behaviour*, which involves a painful execution of a sequence of steps to achieve a goal. More in detail, this behaviour occurs in situations where an obstacle preventing achievement of the goal must initially be removed (Piaget, 1953; Bruce et al., 2009). In this context, the *Carolina Curriculum* (CC) described in the books *Carolina Curriculum for Infants and Toddlers with Special Needs* (CCITSN) (Johnson-Martin et al., 2004a) and *Carolina Curriculum for Preschoolers with Special Needs* (CCPSN) (Johnson-Martin et al., 2004b) is a well established curriculum-based assessment for young children with disabilities. The advantages of the CC are intrinsically clear and well established. In 2006, in Italy, the CC has been adopted as a basic service within several local Regional Service Systems (ASL) (see (Del Giudice et al., 2006)). In (Cuomo et al., 2011), a full web application software system, named *C@rolin@* and based on the CC protocol for Infants and Toddlers, was presented. Unfortunately, this software have presented weaknesses in the assignment of scores in the medical protocol. The aim of this work is to develop a mathematical model for the assignment of consistent scores. Moreover, we have checked the idea on a phantom database of patients and our methodology is under revision of medical staff. In a first feedback, doctors have assured us that the scores are assigned in a consistent way. The work is organized as follow: in Section 2 we recall the history of the CC; in Section 3 we discuss the estimate of age level scores; in Section 4 we deal with some application of the model; finally, the conclusion are drawn in Section 5.

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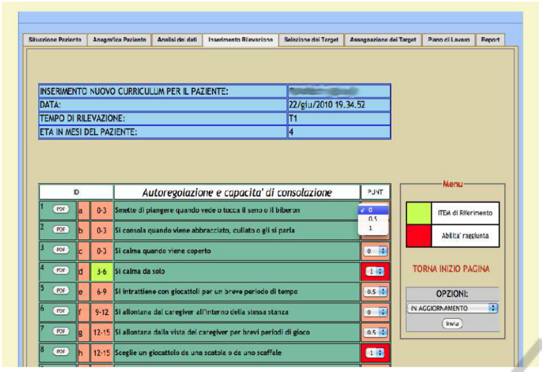

Figure 1: The child curriculum panel.

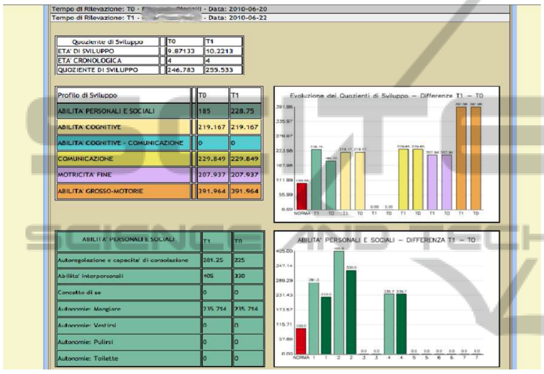

Figure 2: The Data Report Panel.

Figure 3: Web Based Social interaction module.

2 PRELIMINARIES ON THE CAROLINA CURRICULUM

In Figure 1 and Figure 2 we recall the main features of the Carolina software system. This software allows, from one side, to efficiently collect, represent, and evaluate the relative data along the curriculum and, from the other side, to support educators, doctors, volunteers and therapists in the assessment-intervention process of the children involved.

Moreover, the Carolina software allows all medical operators involved in the process of the children development skills to have a concurrent and real-time access to all data, with respect to their own access privileges and to add, modify, elaborate and organize them. Unfortunately the software presented in (Cuomo et al., 2011) takes care only of the medical aspects, which are basically recorded with a huge gap of time intervals; to overcame the problem of the Carolina protocol, a Social Network Framework (Fig. 3) for the Carolina software and consequently an App (Fig. 4) has been developed and showed, respectively, in (Cuomo et al., 2012) and (Cuomo et al., 2014).

Although the medical operator records patient assessments at intervals of 6 months, families and children can now communicate, ask questions and post experiences on the software, thanks to the social networking service embedded in the Carolina software; but the mathematical formulas implemented in order to estimate age levels, still concerns many doctors. This paper proposes a new framework for the mathematical beyond the CC. Before presenting this model, let us briefly examine what is the type of mathematical problem that need to be solved in the Carolina Software.

After the recoding of the assessment, each operator wants to calculate:

- the development age,
- the development rate, and
- the partial performance index of the applied program, for each domain and sequence.

This operation is performed by applying specific formulas, each one developed in a specific module of the software (cf. (Cuomo et al., 2011)).

Prior calculating the development age and rate; it is calculated the weight (W) of each item I, as follows

$$W = \frac{TAP}{NI}$$

where TAP (*Typical Attainment Period*) is the typical period during which a skill is acquired and NI is the

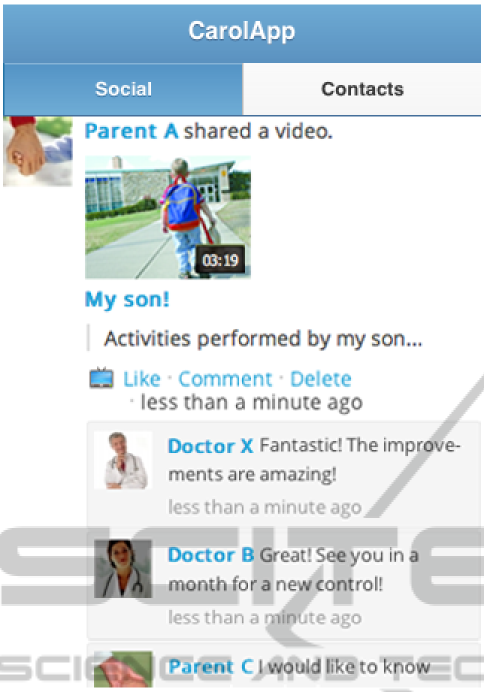

Figure 4: Carol App interaction: Sharing informations.

number of items (i.e. the Possible Points). Hence, the *development age* is obtained by

$$DA = RS \cdot W \tag{1}$$

where RS is the *row score*. The *development rate* is

$$DR = \frac{DA}{CA} \cdot 100 \tag{2}$$

where CA is the *chronological age*. Finally, the partial *performance index* (IP) of the applied program is equal to the performance between two subsequent evaluations. Formally, it is expressed by the following formula

$$IP = \frac{DA(t_n) - DA(t_{n1})}{T}$$

where T is the intervention time. Among these formulas, what mostly concerns doctors, is the fixed weight formula that can bring to an inaccurate estimate of the age level. In fact, doctors, have reported that the estimated development age are meaningful when the child evaluation is done at the beginning or at the end of the age span of each group of items described in the CC. Notice that each formula is based on the previous one, and great effort will be addressed in laying the best foundation for these formulas, i.e. the calculation of *age levels in the board domains*.

In order to correctly develop a mathematical formulation of the equations that will be used in the Carolina software, we will construct such formulation, by taking into account all the possible information from the Carolina Curriculum books (cf. (Johnson-Martin et al., 2004a) and (Johnson-Martin et al., 2004b)). In this Section we will present some useful extracts from the books, and use this informations in order to define the mathematical terms that will be used in Section 3, when we will construct the new mathematical formulation.

2.1 The Carolina Curriculum

Both the CCITSN and the CCPSN are divided into 24 *logical* teaching sequences covering 5 development domains. These two books, starting from the third edition of the CCITSN, are designed to provide a guide for working with children who have special needs from birth to 60 months. The sequence and the item names of the infant and the toddler curriculum are identical in both volume for the 24− to 36−month range. Such continuum makes it possible for this article to address the mathematical formulation for the entire CC, by making possible also an extension for the software to the 60−months period.

Let us introduce the main terms used the CC. The 5 Development Domains are

1. Personal-Social,
2. Cognition,
3. Communication,
4. Fine-Motor,
5. Gross Motor.

Each domain is divided into sub-domains, called Curriculum Sequences (or logical teaching sequence). More specifically, a logical teaching sequence is a sequence of *items* and each item identifies a particular skill that the child should acquire and express. Note that three sequences:

1. Concepts/Vocabulary: Receptive,
2. Concepts/Vocabulary: Expressive,
3. Attention and Memory: Auditory,

are listed as Cognition-Communication. The skills assessed in these sequences are included on almost all tests of cognitive abilities and almost all tests of language abilities. Thus, the three sequences belong to the Cognition domain, as well as the Communication domain; so they should be included in both when estimating a summary level of development for those domains.

More in depth, a *Curriculum Sequence* is a sequence in which item order is primary determined by how one skill builds in another, not only by the mean age levels at which typical children learn the skill. In fact, the items within each curriculum sequence are listed in the order of their expected development. Each item lists criteria for determining when the child has sufficiently mastered a skill and can move to more advanced skill. Finally, in each curriculum sequence items are grouped in *age span*, i.e. an interval time expressed in months that is a multiple of 3. So, each sequence is divided in to multiple *items* (so called in the CC) that are *age-dependent*, i.e. each item describes a *skill* that a child should acquire in a predetermined month interval. Each item is a precise ability that the child has to prove he knows how to do it.

2.2 Definitions

The CC does not assume that a child will develop at the same rate across domains and the skills belonging to a domain are *unrelated* to skills belonging to other domains. We can study a generic domain, calculate the age level in that domain, and then apply the formulas to all the domains of the CC.

We will define the observation of a skill expressed by each item as s_i and each item can have value 0, 0.5 or 1 accordingly that the observers deduce that the child does not have that skill, he quite has it, or he definitely has the skill. This is made in accordance with the convention of the Assessment Log, which states to tag each item with a *plus* $(+)$ for skill the child has mastered, a *plus/minus* $(+/-)$ for an inconsistent or emerging skill, and a *minus* $(-)$ for a skill that the child is unable to do. Observe that a child might have or not the skill in a specific time, so, each s_i must be a function of time t, where the observer, in a particular time, evaluates the skill, so that it will be $s_i(t) \in [0,1]$.

We also define a *chronological age* function, $c(t)$, of the child that is expressed in months (i.e. if the child had 2 years 4 months and 15 day, then we write 24.5 months). The function $c(t)$ is a function of time, that has meaning from the date of birth, db, and will be defined as

$$c(t) = t - db.$$

As for time t we also define an *entering date* t_0 in which we establish the first time, among all the skills, what the child has acquired or not. Then, there will be an appropriate number of *evaluation dates* t_n, where n will vary across the total number of interventions that will be necessary. Moreover at each evaluation date, there will be an Item Rating in which the skills are evaluated: $s_i(t_n)$.

It is important to notice that the skills are age-dependent, and some skill might be linked to ages that are above the chronological age of the child. If they were reported they would indicate some sort of advanced performance of the child, and so an high development rate (DR). To overcome these problems it is important to define more precisely the s_i, and their use in the CC.

Parents, aid and professional, can be considered as the observers of a phenomenon, which is the evolution of a child that is acquiring new skills over time. These observes can not assist this evolution second by second, but at a certain time t_n they observe the child and deduce the level at which the child masters such skill. So the only observables are: the skills s_i and the child chronological age $c(t)$. The second is easily known, but the evaluation of the skills is not so simple. In general, each skill can be considered as a number that can vary from 0 to 1, and is a function of the chronological age, and so a function of time. Each function $s_i(c(t))$ will indicate at a certain time $c(t)$ of the chronological age of the child how much he is able to express that skill, moreover since the linearity of c we will not always indicate such function for the sake of briefness. So we will define a function

$$s_i(t)\colon [0,+\infty) \to [0,1].$$

Next, it is useful to associate at each *observable* function $s_i(t)$, a *standard* function $\bar{s}_i(t)$, which will indicate the typical period to obtain such skill. At this standard functions (as well as to the observable one) we will associate a month n_i indicating when the skill usually arises, and a month m_i that indicates the month, after which the skill is fully developed, and a function $f_i(t)$ that indicates how the skill is obtained in the period $[n_i, m_i]$. This function will be defined

$$\bar{s}_i(t) = \begin{cases} 1, & c(t) \geq m_i \\ f_i(c(t)), & n_i \leq c(t) \leq m_i \\ 0, & c(t) \leq n_i. \end{cases}$$

These hypothesis are consistent with the concept of age span in the CC.

Unfortunately the functions f_i in $\bar{s}_i(t)$ are unknown, and the CC books does not give enough descriptions on how to correctly define such functions; this is reasonable, since the CC is a curriculum-based assessment.

It would be preferable to not fix any sort of hypothesis on f_i, but we will see that in order to evaluate the skill of the child when his age does not coincide with any of the n_i or m_i, we will have to specify f_i, and the simplest hypothesis that we can given is that they are *linear*, i.e.

$$f_i(t) = \frac{c(t) - n_i}{m_i - n_i}.$$

The goal will now be to estimate the age of a child with respect to a particular domain, i.e. $DA(t)$ that will express the development age of the child within a domain. Notice that usually in children with problems we observe

$$DA(t) < c(t).$$

3 AGE LEVEL ESTIMATE

Since we suppose that *the domains are independent*, we will consider a generic domain D. The domain will have a certain number of Curriculum Sequences and each sequence will have a certain number of skills.

We will describe the age estimate related to a generic sequence S, and after it will we straightforward to apply it to our case, consisting of more than one sequence in a domain. It is important to remember, that the *age levels* are *estimates* based on information from standardized instruments and the literature on infant and toddler development. It is not a score based on standardized tests. It is also important to recognize that although standardized tests may provide more accurate age levels (because they are based on larger and more representative samples), these, too, are *estimates* (cf. (Johnson-Martin et al., 2004a)).

The correctness of the proposed formulas will be based on the application of the principles exposed in the Carolina books that we have synthesized in Section 2.1. In additions, many useful comments from operators and doctors, helped us in these formulation.

3.1 Age Estimate in a Sequence

Let us consider a sequence S with NI items. Each sequence will mathematically be a set of functions depending on time, i.e.

$$S = \{s_i(c(t)), \quad i = 1, \ldots, NI\},$$

and the s_i are typically ordered such that $n_i \leq m_{i+1}$.

The skill described in s_1 is typically learned before s_2, s_2 before s_3, and so forth. Moreover, in each curriculum sequence items are grouped in *age span*.

We also know, that ideally, if a child is observed to have mastered s_3 of a sequence and not s_4, it could be assumed that the child has also mastered s_1 and s_2 and will not have mastered s_5 and s_6. A child often practices several related skills at once, however, and there is little consistency as to which skill will emerge first. Furthermore, specific impairments may have different effects on the various skills within a sequence, disrupting the usual pattern of mastery. It is important, therefore, that a sufficient number of items be assessed in each sequence to be certain which skills should be the focus of intervention. As a general rule, the CC advises to continue administering items until the child has passed all at one age span (e.g., 3–6 months) and has not met the criteria at another. In this mathematical formulation, we can suppose that in a certain age span, containing k items, skills that go from s_i to s_{i+k} are all acquired in the time interval $n_i - m_{i+k}$, where the months are known. We know that the development of these skills in such age span results in an overlap of those, but at the same time, with the function s_i, we have given the precise meaning of what skill emerges, i.e. what can be observed. By sticking with this definition, it is possible to suppose that a skill s_{i+1} is *observed* after s_i, by giving foundation to the hypothesis that the order in the set S is given by the property: $n_i \leq m_{i+1}$.

Let us consider a child, whose age $c(t)$ coincides with a fixed month $c(t) = m_k = n_{k-1}$, and suppose that $\min n_i = 0$. In this case, if we are interested in the development age in a specific domain, as a first approach, we can do a weighted average of all the skills and multiply by the actual age, i.e.

$$DA(t) = \frac{\sum_{i\in\Theta(t)} s_i(t)(m_i - n_i)}{\sum_{i\in\Theta(t)} (m_i - n_i)} \cdot m_k$$

where the set $\Theta(t)$ is defined as

$$\Theta(t) = \{l : c(t) \geq m_l\} \neq \emptyset,$$

while we fix $DA(t) = 0$, if $\Theta(t) = \emptyset$.

This average, that uses the set Θ, does not consider skills that are above the chronological age of the child, and so preventing the reporting of an high development quotient, and so solving one of the reported problems noticed by medical operators in the first versions of the software.

Now if we would like to evaluate a child whose age is in between the typical interval of acquiring a skill in a sequence, then we need to use the function f_i, and so

$$DA(t) = \frac{\sum\limits_{i\in\Theta(t)\cup\theta(t)} s_i(t)(m_i - n_i)}{\sum\limits_{i\in\Theta(t)} (m_i - n_i) + \sum\limits_{i\in\theta(t)} f_i(t)(m_i - n_i)} \cdot c(t) \tag{3}$$

where $\theta(t) = \{l : n_l \leq c(t) \leq m_l\}$. If we suppose that $f_i(t)$ is linear then (3) becomes

$$DA(t) = \frac{\sum\limits_{i\in\Theta(t)\cup\theta(t)} s_i(t)(m_i - n_i)}{\sum\limits_{i\in\Theta(t)} (m_i - n_i) + \sum\limits_{i\in\theta(t)} (c(t) - n_i)} \cdot c(t),$$

and we simply have the *Development Rate*

$$DR(t) = \frac{DA(t)}{c(t)} \cdot 100\%$$

which is always less than 100%.

Now if we wish to consider a Sequence whose $\min n_i \neq 0$, then it is more convenient to start defining $DR(t)$, by

$$DR(t) := \frac{\sum_{i\in\Theta(t)} s_i(t)(m_i - n_i) + \sum_{i\in\theta(t)} s_i(t)(m_i - n_i)}{\sum_{i\in\Theta(t)} (m_i - n_i) + \sum_{i\in\theta(t)} (c(t) - n_i)}$$

or more in general we can define

$$DR(t) := \frac{\sum_{i\in\Omega(t)} s_i(t)(m_i - n_i)}{\sum_{i\in\Omega(t)} \bar{s}_i(t)(m_i - n_i)}$$

where $\Omega(t) = \{l : c(t) \geq n_l\}$. Then, by introducing $N := \min n_i$, we can define

$$DA(t) := N + DR(t) \cdot (c(t) - N).$$

This part settles the problem of determining the age of the child in one generic sequence.

Let us compare the new formulation with the method previously implemented in the *Carolina Software* (cf. (Cuomo et al., 2011)). We rewrite the proposed formula for the Development Age, (1),

$$DA = N + \sum_i s_i \cdot \frac{c(t) - N}{NI}, \qquad (4)$$

in fact, this formula says that $RS = \sum_i s_i(t_n)$, and $TAP = c(t) - N$. Since in general we have that

$$DA(t) = N + \frac{\sum_{i\in\Omega(t)} s_i(t)(m_i - n_i)}{\sum_{i\in\Omega(t)} \bar{s}_i(t)(m_i - n_i)} \cdot (c(t) - N) \qquad (5)$$

we can observe that the two equations (5) and (1) the same if we consider two assumptions:

H1 the chronological age coincides with the maximum development age of the Sequence, i.e.

$$c(t_n) = \max_{i=1,\ldots,NI} m_i;$$

H2 the intervals in which the skills are obtained have all the same length, i.e.

$$m_i - n_i = L, \qquad \forall i = 1,\ldots,NI.$$

In fact, under **H1** and **H2**, we have

$$\frac{\sum_{i\in\Omega(t_n)} s_i(t_n)(m_i - n_i)}{\sum_{i\in\Omega(t_n)} \bar{s}_i(t_n)(m_i - n_i)} = \frac{L \cdot \sum_i s_i}{L \cdot NI}.$$

This proves that the new formulation proposed in this paper is an extension of the previously used one, that was meaningful under specific assumptions.

Let us end this section with some observations on the proposed formulas of *DR* and *DA*, with respect of the previous ones. In the new proposed model there are two information that can not be deduced by the CC books. The first one is the formulation of f_i, the second one is how to determine all the months n_i, m_i, $\forall i = 1,\ldots,NI$. Both of these need further assumptions. In the first case we can suppose that the skill of each item evolves linearly. In the second case, the CC only states the age span, and the number of items contained in each of them, and one simple approximation is to suppose the month interval in which such skill usually arise are equally distributed. In this case, if there are $k+1$ skills in an age span, then the time interval will be $[n_i, m_{i+k}]$, where n_i and m_{i+k} are the only given months from the CC books, and it is possible to fix

$$n_{i+j} = \frac{j}{m_{i+k} - n_i} = m_{i+j-1}, \quad \forall j = 1,\ldots,k.$$

Notice that this formulation adheres to the hypothesis that $n_i \leq m_{i+1}$. More advanced formulations, can take into account overlapped skills, and appropriate modifications on the function $f_i(t)$.

3.2 Age Estimate in a Domain

Since we can not tell that the Sequences within a particular Domain are independent of one another, we should calculate the Development age not as a combination of the ages estimates in each Sequence age but considering the items in every Sequence of a domain all together. So let us introduce a Domain D with d Sequences S_i,

$$D = \bigcup_{i=1}^{d} S_i,$$

and each Sequence will have NI_i items, i.e.

$$S_i = \{s_{ij}(c(t)), \quad j = 1,\ldots,NI_i\},$$

where we have added a second subscript to $s(t)$, in order to indicate to which Sequence it belongs.

From the previous section the Development Rate for each Sequence S_i is

$$DR_i(t) := \frac{\sum_{j\in\Omega(t)} s_{ij}(t)(m_{ij} - n_{ij})}{\sum_{j\in\Omega(t)} \bar{s}_{ij}(t)(m_{ij} - n_{ij})},$$

but if we want the same relation, in general among all the skills of a Domain, we should define

$$DR(t) := \frac{\sum_{(i,j)\in\Phi(t)} s_{ij}(t)(m_{ij} - n_{ij})}{\sum_{(i,j)\in\Phi(t)} \bar{s}_{ij}(t)(m_{ij} - n_{ij})}$$

where $\Phi(t) = \{(k,l) : c(t) \geq n_{kl}\}$. From this we simply have

$$DA(t) = DR(t) \cdot c(t),$$

notice that there is no need to introduce N, since in each domain of the CC, at least one Sequence starts from $n_1 = 0$.

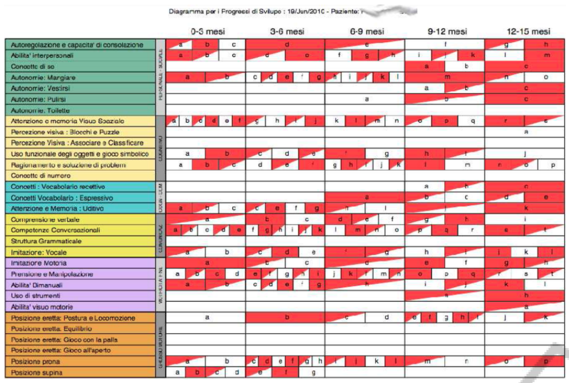

Figure 5: A Develop Progress Diagram (DPD). Blank cells correspond to score 0 ($-$), red cells are equal to score 1 ($+$), the remaining ones to score 0.5 ($+/-$).

4 MATHEMATICAL MODEL APPLICATIONS

For the selection of the emerging skill, in order to create a *planner* (Fig. 5) that draws the skills it is required the experience of the doctor. Here, we propose useful tools to aid doctors in their selection.

Let us address how to select the emerging skill. There is the calculation of the *SS score*, which is done by $DA-N$. Then the doctor can observe the DR, calculated as in (2), and finally ther is a *Percentage Delay*, calculated as

$$PD = \frac{DA-CA}{CA}$$

and among all the Section of a Domain the *median values* are calculated.

Then an emerging skill is selected in the Sections that have a low Percentage Delay and also a low DR. After the doctor proposes a target development rate DR, which is higher than the calculated DR, and finally the doctor decides by whom the child must be helped to improve such skill. In fact, the doctor discusses with the parents and the caregiver of the child, about their goals in a long and short period, and eventually the doctor selects with the parents their next goal.

Although in general such approach is meaningful, it has the same flow as in the calculation of the development rate. As the development rate becomes higher than 100%, at the same time, the Percentage Delay is bigger than 0%.

So, if we simply apply the proposed calculation of the $DR_i(t)$ in some sequence S_i, then we have a development age $DA_i(t)$, and we can define the Percentage Delay

$$PD_i(t) = \frac{DA_i(t)-c(t)}{c(t)}.$$

Then the sections S_i on which the doctors can focus on are the ones whose $PD_i(t)$ is minimum. Most of the used formulas should be correct, as long as one appoints the proposed formalization of DA. There is, for example, an Intervention Efficiency Index Summary Report. The partial performance index of the applied program is defined as

$$IP = \frac{DA(t_n)-DA(t_{n+1})}{T}$$

where T is therapy time. This formula is consistent as long as one uses the proposed formulation of the Development Age.

All the proposed formulas are implementable in the Application Tier of the Carolina software, and so on its mobile version *CarolApp*. In a first implementation, such changes in the software are made only in the *business logic* of the application, by having direct improvements on the resulting age level estimates, and can be viewed in the Data Report Panel as in Figure 2. These changes are reflected in the Use Case Diagram (Figure 6), from a software system point of view, where we highlight the new features introduced for the mathematical model. The improvement is made in the Carolina web based features, by modifying the *Statistical Report* module, that generates all the data that after are viewed by the doctor through the *View Data* module.

In addition, new options can be added to the Client Tier within the doctor's related interface. This layer

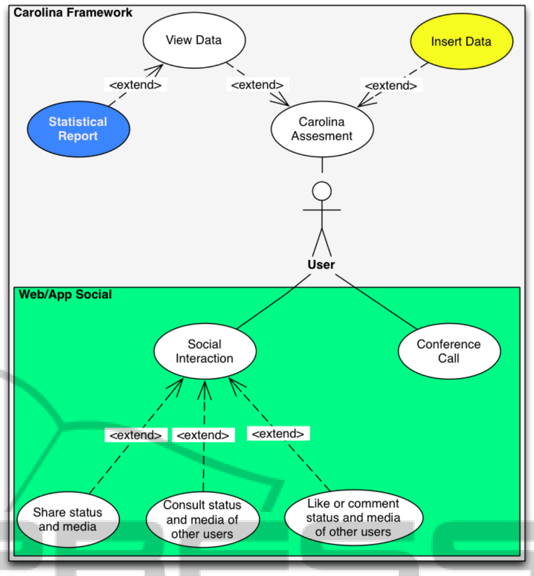

Figure 6: Use case Diagram.

can be modified, in order to give more options to the medical operators that can change the free parameters in the estimate, accordingly to their personal experience and sensibility, to obtain a more accurate estimate. These add-on could make the difference in case of very sparse and scattered skills.

Finally, thanks to this mathematical framework that improves the calculation of age estimate, it is possible to enhance the partial performance index. This index indicates how well the child did in a time interval, supposing that doctors have programmed the intervention, and parents with operators have followed such program. Thanks to this index, and a database storing a vast amount of child cases, a machine learning algorithm can be applied to help doctors in improving their intervention program, by opening a research line to build up a system that can support them during their decisions.

5 CONCLUSIONS

The Carolina is a software framework developed to implement the Carolina Curriculum for Infants and Toddlers with Special Needs. The software has evolved over the years, moving from a client-server application to a software system integrated with social network features.

In this work, we have developed a mathematical model for the assignment of consistent scores. We have overcome the main obstacle to give a cognitive age value to the children that enter the curriculum in different times of the medical protocol. This is a crucial point because the entire program assessment is a sequential medical procedure that goes on step by step. The mathematical model is tested on a phantom database of patients and is in advanced stages of experimentation and doctors have assured us that the scores are assigned in a consistent way. Future works will be devoted to finish the test and the deploy of the entire system and analyze more complete and interesting experimental results about the real advantages of the proposed mathematical model also considering real data.

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